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IMPROVING TRANSPORT LOGISTICS OF EXTRACTIVE INDUSTRY PRODUCTS IN THE CONTEXT OF CAPACITY CONSTRAINTS ON THE RAILWAYS

Purpose. To improve the distribution methods of freight flows on the railway network under conditions of capacity constraints.

Methodology. Methods of railway operation theory and operations research were used. The problem of cargo flow distribution on the railway network was solved as a multi-product (interchangeable cargoes) transport linear programming problem with capacity constraints in the network form. The average cost of freight transportation is established by the methods of probability theory.

Findings. In the course of the research the methods of cargo traffic calculation on the railway network are improved. The proposed approach to the formalisation of the task makes it possible to take into account the presence of different cargoes to be transported, capacity constraints of some railway network sections, as well as non-linear nature of dependence between the volume and cost of transportation. To meet the requirement of consignors' equal access to public carrier services, the method for calculating the cost of transportation for an individual consignor is improved.

Originality. Scientific novelty of the paper consists in improvement of methods of cargo traffic distribution on the railway network and tariffing of cargo transportation services in conditions of restricted supply capacity of separate sections.

Practical value. The extractive industries have a steady flow of goods. The main logistic tasks in this case are to ensure transportation of the given volume of cargo and reduce the cost of transport services. Using the proposed mathematical methods of optimization allows you to get higher-quality solutions compared to the method of technical-economic comparison of options, which provides an overall cost reduction for cargo transportation. The improved method of tariffication of transportation can reasonably allocate the savings from reducing the cost of transportation among cargo consignors and thus reduce their logistics costs.

Keywords: *railway transport, cargo transportation, transportation planning, transportation problem*

Introduction. Rail transport is the main carrier of cargo both in the Republic of Kazakhstan and in Ukraine. In 2021 rail transport accounted for 50.1 % of Kazakhstan's freight turnover and 62.2 % of Ukraine's freight turnover. The main cargo transported by rail transport in both countries is products of the mining industry [1, 2]. Coal, ores of ferrous and non-ferrous metals, as well as construction cargo account for about 66 % of all cargo transported by rail in Kazakhstan and about 61 % in Ukraine. The specified types of products of the extractive industry form massive, fairly stable over time, cargo flows, the transportation of which requires the allocation of a significant capacity of the railways. At the same time, these goods are relatively cheap, and the transport component is 30–50 % of their cost for the end user. Therefore, improving the efficiency of railway transport [3, 4] is important for the economy of both countries as a whole and for individual enterprises of their mining complex as well [5].

Currently, in many countries of the world there is a division of the rail transportation market into natural monopoly and competitive sectors. These changes lead to the emergence of railway infrastructure services that differ in terms of cost and quality. The demand for such services from railway customers is determined by the fact that they allow optimizing logistics costs in their supply chains. The offer of railway infrastructure is formed on the basis of the topology and technical equipment of the network. Therefore, research aimed at developing methods for finding a rational distribution of cargo flows on the railway network, taking into account the cost of transportation and the constraints of the capacity of railway infrastructure elements, is relevant.

Literature review. Currently, in Kazakhstan and Ukraine, transportation of goods by rail is organized on the basis of a plan for the formation and schedule of trains. Development of a plan for the formation and schedule of train traffic are optimization tasks [6, 7], the solution of which should ensure the development of planned traffic volumes with minimal operating costs, while unconditionally meeting the requirements for the safety of train traffic [8].

The distribution of carriage traffic on the railway network is one of the stages in the development of a plan for the formation of trains. In the course of solving this problem, the most cost-effective directions for the movement of carriage traffic are determined to provide a minimum of costs for the moving, formation and disbandment of trains. In addition, for possible directions, the time for passing sections and stations by carriages, fuel consumption for shunting work, as well as the throughput of sections and the processing capacity of stations are estimated. In practice, the choice of directions for the carriage flows on the railway network is carried out on the basis of a technical and economic comparison of the selected options. This approach is associated, firstly, with a significant degree of subjectivity in the selection of options for comparison, and secondly, it does not provide equal and non-discriminatory access for shippers to the services of a public carrier and carriers to the services of a public infrastructure manager. In this regard, the methods of distribution of carriage traffic on the railway network require improvement.

The task of distributing carriage traffic on the railway network, both as a whole and its individual elements, is widely considered in scientific papers. To date, methods for estimating the costs associated with the passage of carriage flows along railway sections and directions and their processing at stations, methods for estimating the capacity of individual elements of the railway infrastructure and the network as a whole, method for distributing flows on the railway network have been developed.

The cost for the passage of carriage flows along the railway sections and for their processing at stations is currently set using the cost rate method. To this end, on the basis of data from industry statistics, railways calculate expenditure rates associated with certain physical measures of their work. Further, on the basis of the predicted values of physical measures of work and expenditure rates for the measure, an assessment of the cost of transportation is performed. In general, if there is a qualitative forecast of physical measures of the work of railway transport, it is now possible to obtain a reliable economic estimate of the planned cost of transportation.

One of the main factors influencing the distribution of carriage traffic on the railway network is the limitation of the capacity of the railway infrastructure. A detailed critical analysis of the criteria and methods for assessing the capacity of the railways of Western Europe and North America is made in the work by Pouryousef, et al. [9].

The capacity of railway sections in the countries of the European Union and in the UK is measured by the number of trains of a certain category that can be passed through the railway infrastructure per unit of time. A feature of the work of railway transport in Western Europe is that the predominant share of both freight and passenger trains follows the schedule. The main methods for assessing the capacity of railways in Western Europe are the UIC 406 method used in the European Union [10] and the CUI method used in the UK [11]. Both methods are based on schedule compression, in which the current schedule paths are transferred within the considered time interval so that the inter-train intervals are reduced to the minimum allowable values. In conditions of a non-uniform train flow, the assessment of capacity is a rather difficult task, which has not been finally solved. Currently, research is on-going aimed at improving the methods for constructing motion schedules. In particular, in [12] a method has been proposed by Arani at al. to increase the number of train lines on the graph compared to UIC 406.

In North America, the vast majority of rail traffic is on trains that depart without following a strict timetable. In the United States and Canada, to assess the capacity of railway sections, the relationship between the degree of filling of the capacity of the line and the delays that occur when trains pass is used. In particular, such an approach is illustrated in the work by Dick, at al. [13]. The data presented in [13] show that with an increase in the degree of capacity filling the average value of train delays increases non-linearly and the flexibility of the schedule decreases.

In Kazakhstan, Ukraine and other post-Soviet countries, rail transport is used both for transportation of passengers and for transportation of cargo. At the same time, passenger trains follow a strict schedule, while freight trains follow accumulation. The capacity of railway sections is estimated by the number of freight trains that can be passed in addition to regular trains (passenger, suburban, groupage, etc.), similarly to how it is done in Western European countries. Studies to assess the relationship between the degree of filling capacity and the quality indicators of rail transport in the post-Soviet countries are also being carried out. Examples of such works are the papers by Bobrovsky, at al. [14] and Burakova & Ivankova [15]. However, in practice, as a rule, such calculations are performed only when solving problems of railway development.

Currently, in most cases, the railway infrastructure is organized into complex networks. And this fact leads to a number of optimization problems. Works by Besinovic & Goverde [16] and by Weik, at al. [10] are devoted to the adaptation of UIC 406 methods for estimating the capacity of railway sections in combination with the capacity of railway junctions. It should be noted that in the conditions of Kazakhstan and Ukraine, the issues of railway capacity are important, but not critical. In general, the railway networks of both countries have reserves of capacity, although some sections of the railway infrastructure are heavily overloaded due to the concentration of freight traffic on them. In this regard, the issue of rational distribution of flows on the network is relevant.

In [17], the problem was studied of the distribution of carriage traffic on the network, some sections of which are screwed up by different infrastructure managers interested in maximizing the profit from transportation. The model proposed in [17] can be used to analyse the operating conditions of the railway network in the system of international transportation or in the conditions of competition between railway and other modes of transport. For domestic rail transport, its use is not practical, as it is assumed that there is a single infrastructure manager in Kazakhstan and Ukraine.

The paper [18] considers the problem of optimizing the number and location of cargo loading points on the railway network in order to minimize transportation costs. In this study, unlike most known works, the position of the points of departure and destination of goods is fixed.

The paper by Vernigora, at al. considered the problem of distributing the transportation of iron ore and metallurgical products between parallel directions of the railway network. One of the assumptions adopted in is that the same type, interchangeable cargo is transported on the network. This assumption allows us to reduce the problem of distribution of cargo flows on the network to the solution of a nonlinear transport problem with restrictions on the capacity, which was done. However, from the position of the railroad, this assumption is not valid in the way that the railroad performs transportation (provides the carrier with a schedule path) between the specified consignor points.

An important factor that must be taken into account when organizing the interaction of public railways and their customers is that customers are separate entities, each of which strives to optimize their logistics costs. Each individual enterprise can either independently solve the problem of transport logistics by building routes for the transportation of its products with all key points, or transfer this function to the carrier, and determining only the start and end points. Therefore, methods based on the optimization of total transportation costs should not only provide a systemic effect, but also take into account the interests of individual customers. In accordance with the studies performed in the paper by V. Zitricky, et al. [19], infrastructure managers allocate two types of paths to carriers:

- "regular train path" – regular train path is used by all regular trains; trains go by the schedule (train diagram) at least once a week on the specified day;
- "ad hoc train paths", this train path is used by all extraordinary trains.

According to [20], the share of more expensive "ad hoc train paths" is about 40 % of the allocated schedule paths. This indicates the fact that the effect of pre-planning transportation does not always provide a reduction in the logistics costs of individual carriers.

Purpose. The purpose of this paper is to improve the methods of distribution of cargo flows on the railway network in conditions of limited capacity.

Methods. The solution of the problem of distribution of cargo flows on the railway network is based on the use of operations research methods. When formalizing the problem, the following assumptions were made. The railway network is represented by a directed graph $G(V, E)$, whose vertices $v_i \in V$, $I = n$ (here n is the number of graph vertices) correspond to the consignors, consignees and transit points of the network, and the arcs $e_j \in E$, $j = m$ (here m is the number of arcs of the digraph) correspond to the sections of the network between the vertices. It is assumed that K types of cargo are transported on the network, following between the given vertices of departure and destination. The entire set of vertices is divided into three subsets S, B and T so that the vertices $s_k \in S$, $k = 1 - K$ correspond to the consignors; vertices $b_k \in B$, $k = 1 - K$ correspond to consignees; vertices $t_i \in T$, $I = n - 2K$ are transit. Each pair of vertices of consignors s_k and consignees b_k corresponds to one unique type of cargo, for which the transportation volume F_k is specified. In this case, the volume of cargo for the consignor is $+F_k$, and for the consignee it is $-F_k$. It is accepted that the transportation of goods is carried out in batches. Therefore, the F_k values can only take integer values. If some consignor sends several types of cargo or the consignee receives several types of cargo, then they are assigned a group of transit vertices and vertices of consignors and/or consignees connected to it by fictitious arcs. The graph arcs $e_j \in E$ correspond to railway sections. For each of the arcs, the initial u and final v vertex is indicated. Each arc is assigned the cost of transportation c_j and, if necessary, the value of the cargo flow along the arc f_j and the capacity limit d_j. The analysis of the research results presented in [12, 15] shows that the cost of transportation along the railway section increases non-linearly as the line capacity load increases. This is due to the increased demurrage of trains at stations within the section for their crossing with oncoming trains and overtaking trains of higher priority. In addition, with a high degree of capacity, train drivers cannot use the most energy-efficient modes of driving a particular train, since they have to take into account the movement of adjacent trains. To take into account the dependence between the degree of capacity filling and the cost of transportation $c_j(f_j)$ between the initial u and final v vertices of the arc e_j the H_{uv} of arcs with increasing transportation costs and capacity constraint can be specified. Under such conditions, the arcs e_j can be unambiguously designated as $e_{uv,h}$, $h = 1 - H_{uv}$, while the transportation costs are ordered so that $c_{uv,h} < c_{uv,h+1}$, and the throughput of the arcs $h = 1 - H_{uv} - 1$ is necessarily limited.

The process of transportation of cargos between each pair of vertices s_k and b_k is represented by a chain of successive flows on the arcs $f_{uv,hk}$, which represent the variable tasks. The cost of transporting cargo of type k along the arc $e_{uv,h}$ is defined as $c_{uv,h}f_{uv,hk}$. The best distribution of traffic on the network is considered to be the one that provides the minimum total transportation costs.

As a result, the problem of distribution of cargo flows on the network can be formalized as a problem of minimizing the total costs for the transportation of all cargos, defined as a linear objective function

$$C = \sum_{u=1}^{V}\sum_{v=1}^{V}\sum_{h=1}^{H_{uv}}\left(c_{uv,h}\sum_{k=1}^{K} f_{uv,hk}\right) \to \min, \qquad (1)$$

under linear constraints:

- on the volume of cargo dispatch from the vertices corresponding to the consignors $u \in S$

$$\sum_{i=1}^{n}\sum_{h=1}^{H_{ui}} f_{ui,hk} - F_k = 0, \quad k = 1 - K; \qquad (2)$$

- on the volume of cargo arrival at the vertices corresponding to the consignees $v \in B$

$$\sum_{i=1}^{n}\sum_{h=1}^{H_{iv}} f_{iv,hk} + F_k = 0, \quad k = 1 - K; \qquad (3)$$

- on the volume of departure and arrival of cargo in transit vertices $t \in T$

$$\sum_{i=1}^{n}\sum_{h=1}^{P_{it}} f_{it,hk} - \sum_{j=1}^{n}\sum_{h=1}^{P_{tj}} f_{tj,hk} = 0, \quad k = 1 - K; \qquad (4)$$

- on the total amount of cargo traffic along arcs with limited capacity

$$\sum_{k=1}^{K} f_{uv,hk} \le d_{uv,h}; \qquad (5)$$

- by the size of individual cargo flows

$$f_{uv,hk} \ge 0. \qquad (6)$$

Based on the analysis of the objective function (1) and constraints (2–6) of the presented problem, it can be classified as a special case of multi-commodity transportation problem of linear programming with limited capacity. The proposed approach to the formalization of the problem makes it possible to take into account the presence of various cargos for transportation, the constraint of the capacity of individual sections of the railway network, as well as the non-linear nature of the relationship between the volumes and the cost of transportation.

Results. When solving the problem of distribution of cargo flows on the railway network, the points of departure and destination of goods are known, and the routes of cargo flows are subject to optimization. In this regard, the solution of the problem is performed on a network diagram that reflects the topology and G graph parameters.

The example of a transport network is shown in Fig. 1.

The graph representing the railway network contains 15 vertices, of which vertices 1, 3, 5 and 7 are the vertices of the consignors, vertices 2, 4, 6 and 8 are the vertices of the consignees, vertices 9–15 are transit. The graph has 27 arcs, while the capacity of the arcs $e_{9.10.1}$, $e_{9.10.2}$, $e_{9.13}$, $e_{12.13.1}$, $e_{12.13.2}$ is limited. Four types of cargo are transported on the network.

With such a formalization of the problem, the optimal transportation plan that provides a minimum of transportation costs according to (1) can be obtained by the potential method. When using the method of potentials, a spanning tree is allocated on graph G, representing the basic transportation plan. The basic plan includes arcs with underutilized capacity. The number of arcs in the basic plan is $n - 1$. With a smaller number of arcs, arcs with full capacity or no cargo transportation can be added to the basic plan to obtain the main tree. Potentials A_v represent the conditional cost of transporting goods at the vertices. Potentials are calculated starting from an arbitrary vertex of the basic plan. When moving along the direction of the arc of the basic plan, the vertex potential is defined as

$$A_v = A_u + c_{uv,h},$$

when moving against the direction of the base plan arc, the vertex potential is defined as

$$A_u = A_v - c_{uv,h}.$$

The analysis of the potential difference $\Delta_{uv} = A_v - A_u$, as well as the cost of transportation along the arcs cuv,h, allows us to evaluate the optimality of the transportation plan. In particular, if the condition $\Delta_{uv} > c_{uv,h}$ is satisfied for arcs with unfilled capacity, then the transportation plan can be improved by including the arc $e_{uv,h}$ in the basic plan and redistributing cargo flows. If for some arc with a fully occupied capacity the condition $\Delta_{uv} > c_{uv,h}$, is met, then the value $\delta_{uv} = \Delta_{uv} - c_{uv,h}$ indicates the cost savings when passing cargo along an arc with a fully occupied capacity compared to the basic plan. The solution of a single-product transport problem on the network consists in constructing an arbitrary basic transportation plan and its successive improvement until the condition $\Delta_{uv} \le c_{uv,p}$ is satisfied for all arcs with unfilled capacity. The solution of a linear multi-com-

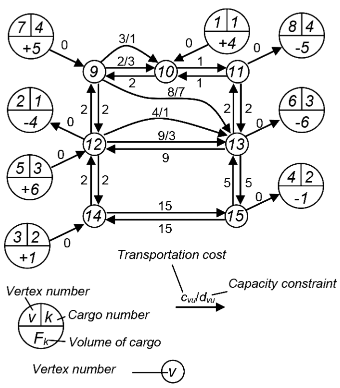

Fig. 1. Representation of the transport network for solving the problem of distribution of cargo flows in the form of a graph

modity transport problem with capacity constraints on the network is reduced to solving single-commodity transport problems. At the same time, cargos are introduced into the transportation plan in stages, and at each stage a single-product transport problem is solved to optimize transportation on the network of the last introduced cargo and the previous cargo associated with it. The method for solving multi-commodity transport problems on a network is described in detail in [20, 21].

The optimal transportation plan that provides a minimum of transportation costs for the example in Fig. 1 is shown in Fig. 2. The total costs of all consignors in the implementation of this plan will be $C = 117$ units.

Transportation of individual consignments is carried out along routes $r_l \in R$ (here l is the conditional number of the route in the set R), which are simple chains of arcs connecting consignors vertices s_k with consignees vertices b_k. The characteristic of the route is the cost of transportation $c_{r,l}$, which is the total cost of transportation along the arcs included in the route.

When distributing traffic to networks in accordance with the plan presented in Fig. 2, the capacity of four arcs ($e_{9.10.1}$, $e_{9.10.2}$, $e_{12.13.1}$, $e_{12.13.2}$) has been completely exhausted. This caused an increase in the cost of transporting cargos 2, 3 and 4 compared to the cheapest routes. An analysis of the resulting transportation plan allows you to set the transportation cost of a unit of cargo along the arcs being a part of the basic plan (maximum allowable cost), as well as along routes that provide a lower cost of transportation, but include arcs with fully utilized capacity. Such routes will be called rational. The Table 1 shows all possible rational routes for the transportation of cargos with the cost of transportation not exceeding the cost of transportation according to the basic plan.

After the distribution of flows on the network it is necessary to solve the problem of distributing the costs of transporting goods between consignors. Table 2 shows the average weighted cost of cargo transportation according to the optimal plan $\bar{c}_{r,k}$ for each of the k^{th} types of cargo. For comparison, the same table for each cargo shows the cost of transporting goods along the shortest routes $\min(c_{r,k})$, as well as the average cost of transporting goods in cases where the allocation of capacity for this type of cargo is performed last $\max(c_{r,k})$.

The use of actual mileage for the tariffing of transportation in the case of a centralized distribution of cargo flows on the network can significantly worsen the conditions for individual consignors. This is due to the fact that the diversion of their flows to less profitable routes may be associated with the need to create better pass conditions for other consignors. In particular, the arc $e_{12.13.1}$, transportation along which provides savings for both cargo type 2 and cargo type 3, was used only for the transportation of cargo type 3. At the same time, all cargo of type 2 is transported along a route that has a higher cost of transportation. Moreover, the cases are quite frequent when there are several optimal transportation plans. In such cases, the choice of the pass route and, accordingly, its cost for a particular consignor is random.

At present, the tariffication of transportation is carried out in accordance with tariff distances (as a rule, the shortest ones). With a simplified approach, in order to switch from transportation

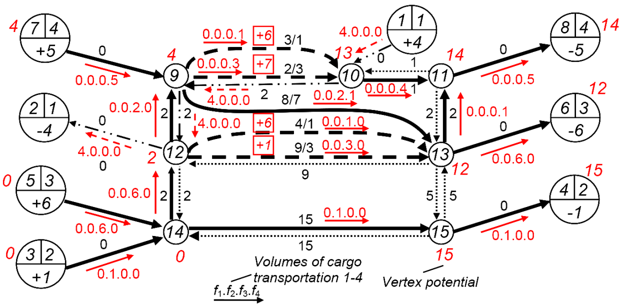

Fig. 2. The optimal plan for the distribution of cargo flows on the network

Table 1

Possible routes for the transportation of cargos on the network

Cargo No.	Route		
	l	Arcs	$c_{r,l}$
1	1	$e_{1.10} - e_{10.9} - e_{9.12} - e_{12.2}$	4
2	2	$e_{3.14} - e_{14.12} - e_{12.13.1} - e_{13.15} - e_{15.4}$	11
	3	$e_{3.14} - e_{14.15} - e_{15.4}$	15
3	4	$e_{5.14} - e_{14.12} - e_{12.13.1} - e_{13.6}$	6
	5	$e_{5.14} - e_{14.12} - e_{12.9} - e_{9.10.1} - e_{10.11} - e_{11.13} - e_{13.6}$	9
	6	$e_{5.14} - e_{14.12} - e_{12.9} - e_{9.10.2} - e_{10.11} - e_{11.13} - e_{13.6}$	10
	7	$e_{5.14} - e_{14.12} - e_{12.13.2} - e_{13.6}$	11
	8	$e_{5.14} - e_{14.12} - e_{12.9} - e_{9.13} - e_{13.6}$	12
6	9	$e_{7.9} - e_{9.10.1} - e_{10.11} - e_{11.8}$	3
	10	$e_{7.9} - e_{9.10.2} - e_{10.11} - e_{11.8}$	4
	11	$e_{7.9} - e_{9.13} - e_{13.11} - e_{11.8}$	10

Table 2

Estimation of the actual cost of transportation of cargo according to the optimal plan for the distribution of cargo flows

k	Transportation costs			$\frac{\bar{c}_{r,k}}{\min(c_{r,k})}$	$\frac{\bar{c}_{r,k}}{\max(c_{r,k})}$
	$\min(c_{r,k})$	$\max(c_{r,k})$	$\bar{c}_{r,k}$		
1	4.0	4.0	4.0	1.00	1.00
2	11.0	15.0	15.0	1.36	1.00
3	6.0	11.5	10.5	1.75	0.91
4	3.0	10.0	4.6	1.53	0.46

pricing based on actual mileage to transportation pricing based on tariff distances, it is necessary to calculate the coefficient

$$\gamma_t = \frac{C}{C_{\min}},$$

where $C_{\min}$ stands for the total cost of transporting all cargos in the absence of constraints (5).

The cost of transporting a consignment of cargo from a separate consignor is calculated as

$$c_{rt,k} = \gamma_t \min(c_{r,k}).$$

For the example shown in Fig. 1, $C_{\min} = 78$ units. As a result, $\gamma_t = 1.5$. Comparison of the actual cost of transportation and the cost of transportation calculated for the shortest distances is given in Table 3.

Analysis of Fig. 2 and Table 3 shows that the cost of transportation for consignors 2 and 3 is calculated along the $e_{12.13.1}$ arc with the capacity that is significantly lower than the traffic volumes. In many cases, such arcs on the railway network correspond to secondary sections that do not have development prospects. Also, the data in Table 3 show that the cost of transportation for consignors 1 and 2 is significantly overestimated. Moreover, consignor 1 bears the costs associated with the lack of capacity of sections of the railway network, which he cannot even use. In general, the approach to tariffing transportation on networks with limited capacity along the shortest route leads to an overestimation of the transportation cost of individual consignors and, as a result, either to their transition to alternative modes of transport, or to the uncompetitiveness of their products compared to other suppliers.

To overcome these problems, it is proposed to carry out the distribution of cargo flows on the network under the condition that all consignments of goods included in the transportation plan have equal opportunities to occupy the capacity of the arcs. When a consignment is delivered for transportation, it

Table 3

The cost of transportation of cargo established on based on the shortest transportation routes

k	cost of transportation		
	$\min(c_{r,k})$	$c_{r,k}$	$c_{rt,k}$
1	4	4.0	6.0
2	11	15.0	16.5
3	6	10.5	9.0
4	3	4.6	4.5

is passed along the shortest unused route. For the conditions of transportation of 1 unit of cargo 2, 6 units of transportation of cargo 3, and 5 units of transportation of cargo 4 given in the example, there are 5,544 options for combinations of their receipt. Transportation of shipments of cargo 1 is not related to the transportation of other types of cargo; therefore, they are not taken into account in the distribution of capacity. The calculation of the cost of transporting goods, based on the assessment of the probabilities of occupying routes p_l, is given in Table 4. In this case, the average cost of transportation of cargo of type k is calculated by the formula

$$\bar{c}_{rp,k}=\sum_{l} p_l c_{r,l},$$

and the total cost of transporting the k^{th} type of cargo according to the formula

$$C_{p,k}=\bar{c}_{rp,k}F_k.$$

The total cost of transportation of cargoes 2–4 when providing them with the shortest possible routes in the order of receipt of applications will be C_p = 108.62 units, and if the distribution of these cargoes on the network is optimized, C^* = = 101 units. The resulting coefficient is

$$\gamma_{op}=\frac{C^*}{C_p}=\frac{101.00}{108.62}=0.93,$$

it is proposed to use for tariffing the transportation of goods 2–4, which use interconnected sections with exhausted capacity. The cost of transportation of cargo k is proposed to be determined as

$$\bar{c}_{ro,k}=\bar{c}_{rp,k}\gamma_{op}.$$

The calculation of the cost of transporting goods, as well as the total costs of consignors, is given in Table 5.

The results obtained show that centralized planning of cargo transportation in the presence of sections with a high level of capacity utilization will allow railways to use their technical potential more efficiently. At the same time, the rational distribution of traffic along parallel routes makes it possible to reduce the cost of transportation and provide services to consignors at more competitive prices. Regarding the transportation of products of mining enterprises, it should be noted that they are sensitive primarily to the cost indicator and do not have high requirements regarding delivery times. In this regard, after developing a centralized transportation plan and fixing the cost of services for consignors, the railway can continue to improve the transportation plan according to other criteria, such as delivery times and others.

Table 4

The cost of transportation of cargo, established as based on an estimate of the probabilities of occupying routes

k	*routes*					$C_{p,k}$
	1	$c_{r,l}$	p_l	$p_l c_{r,l}$	$\bar{c}_{rp,k}$	
2	2	11	0.143	1.573	14.43	14.42
	3	15	0.857	12.855		
3	4	6	0.143	0.858	9.86	59.20
	5	9	0.209	1.881		
	6	10	0.089	0.89		
	7	11	0.471	5.181		
	8	12	0.088	1.056		
4	9	3	0.350	1.05	7.00	35.00
	10	4	0.092	0.368		
	11	10	0.558	5.58		
Total						108.62

Table 5

Cargo transportation costs and total costs for consignors when transporting goods on networks with limited capacity of sections

k	Transportation costs		$\frac{\bar{c}_{ro,k}}{\max(c_{r,k})}$
	$\max(c_{r,k})$	$\bar{c}_{ro,k}$	
1	4.00	4.00	1.00
2	15.00	13.42	0.89
3	11.50	9.17	0.80
4	10.00	6.51	0.65

The scientific novelty of the paper lies in the improvement of the methods of distribution of cargo flows on the railway network and the tariffication of services for the transportation of cargo in conditions of limited capacity of individual sections. The solution of the problem is achieved by reducing it to the solution of a multi-commodity transport problem of linear programming with capacity constraints in a network form. The average cost of transportation of goods is established on the basis of an analysis of the probability of their following along various routes. The practical value of the paper consists in the fact that the use of mathematical optimization methods makes it possible to obtain better solutions compared to the currently used method of technical and economic comparison of options, which ensures an overall reduction in the cost of transporting cargos. The improved method for tariffing transportation allows you to reasonably distribute the savings from the reduction in transportation costs between the consignors and, due to this, reduce their logistics costs.

Conclusions. The performed studies allow us to draw the following conclusions:

1. Reforming the rail transportation market requires railways to introduce a range of services that differ in price and quality. One of the types of railway transport services in the conditions of a shortage of infrastructure capacity can be the passage of regular trains on pre-planned routes and the transportation of cargos, if necessary, on routes that are free at the time of application. The demand for such services from railway customers is determined by the fact that they allow optimizing logistics costs in their supply chains. Transportation by trains of regular circulation is especially important for the enterprises of the mining complex of Kazakhstan and Ukraine. On the one hand, these transportations account for more than 60 % of the transportation of all goods and require the allocation of significant capacity. On the other hand, the share of transportation costs in the final cost of these goods is 30–50 %, so the organization of transportation of extractive industry products should ensure the maximum reduction in the cost of transportation.

2. The problem of distribution of cargo flows on the railway network can be reduced to solving multi-commodity linear programming problem capacity constraints. The solution of this problem allows you to develop plans for the transportation of goods, which reduce the average cost of transporting goods on the network. At the same time, the achievement of a minimum of total transport costs on the network can be achieved by transporting goods from individual consignors along routes with a higher cost. Therefore, the reduction in logistics costs of some consignors is partially achieved at the expense of other consignors.

3. The number of rational routes for cargo on the transport network is limited. To ensure the requirement of equal access

of consignors to the services of a public carrier or carriers to the services of an infrastructure manager it is proposed to establish the probabilities of passing goods along rational routes when passing goods along the shortest routes in the order in which applications are received. Based on these probabilities, the distribution of the total minimum transportation costs between the consignors is carried out.

References.

1. Zabolotny, K., Zinovyev, S., Zupiev, A., & Panchenko, E. (2015). Rationale for the parameters equipment for rope dehydration of mining hoisting installations. *New Developments in Mining Engineering 2015: Theoretical and Practical Solutions of Mineral Resources Mining*, 275-281.
2. Dychkovskyi, R., Tabachenko, M., Zhadiaieva, K., Dyczko, A., & Cabana, E. (2021). Gas hydrates technologies in the joint concept of geoenergy usage. *E3S Web of Conferences*, *230*, 01023. https://doi.org/10.1051/e3sconf/202123001023.
3. Samorodov, V., Bondarenko, A., Taran, I., & Klymenko, I. (2020). Power flows in a hydrostatic-mechanical transmission of a mining locomotive during the braking process. *Transport Problems, 15*(3), 17-28. https://doi.org/10.21307/tp-2020-030.
4. Taran, I. A., & Klimenko, I. Yu. (2014). Transfer ratio of double-split transmissions in case of planetary gear input. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu,* (6), 60-66.
5. Zabolotnyi, K. (2017). Development of a model of contact shoe brake-drum interaction in the context of a mine hoisting machine. *Mining of Mineral Deposits, 11*(4), 38-45.
6. Zhuravel, O., Derbaba, V., Protsiv, V., & Patsera, S. (2019). Interrelation between shearing angles of external and internal friction during chip formation. *Solid State Phenomena*, *291*, 193-203. Retrieved from https://www.scientific.net/SSP.291.193.
7. Naumov, V., Zhamanbayev, B., Agabekova, D., Zhanbirov, Z., & Taran, I. (2021). Fuzzy-logic approach to estimate the passengers' preference when choosing a bus line within the public transport system. *Communications – Scientific Letters of the University of Žilina*, *23*(3), A150-A157. https://doi.org/10.26552/com.C.2021.3.A150-A157.
8. Taran, I., & Klymenko, I. (2017). Analysis of hydrostatic mechanical transmission efficiency in the process of wheeled vehicle braking. *Transport Problems*, *12*(Special Edition), 45-56. https://doi.org/10.20858/tp. 12. se.4.
9. Pouryousef, H., Lautala, P., & White, T. (2015). Railroad capacity tools and methodologies in the U.S. and Europe. *Journal of Modern Transportation*, *23*, 30-42. https://doi.org/10.1007/s40534-015-0069-z.
10. Weik, N., Warg, J., Johansson, I., Bohlin, M., & Nieben, N. (2020). Extending UIC 406-based capacity analysis – New approaches for railway nodes and network effects. *Journal of Rail Transport Planning & Management*, *15*, 100199. https://doi.org/10.1016/j.jrtpm.2020.100199.
11. Armstrong, J., & Preston, J. (2017). Capacity utilisation and performance at railway stations. *Journal of Rail Transport Planning & Management*, *7*(3), 187-205. https://doi.org/10.1016/j.jrtpm.2017.08.003.
12. Arani, A. A. M., Jolai, F., & Nasiri, M. M. (2019). A multi-commodity network flow model for railway capacity optimization in case of line blockage. *International Journal of Rail Transportation*, *7*(4), 297-320. https://doi.org/10.1080/23248378.2019.1571450.
13. Dick, C. T., Mussanov, D., & Nishio, N. (2019). Transitioning from Flexible to Structured Heavy Haul Operations to Expand the Capacity of Single-Track Shared Corridors in North America. *Journal of Rail and Rapid Transit*, *233*(6), 629-639. https://doi.org/10.1177/0954409718804427.
14. Bobrovskyi, V. I., Korobyova, R. G., & Balanov, V. O. (2019). Simualtion model for evaluating the carrying capacity of railways. *Science and Transport Progress*, *6*(78), 16-27. https://doi.org/10.15802/stp2018/154819.
15. Burakova, A. V., & Ivankova, L. N. (2017). Complex reconstruction of single track lines in connection with increase in volume of transportations Science and Technology. *Transport*, *4*, 11-14. Retrieved from https://elibrary.ru/item.asp?id=32252925.
16. Besinovic, N., & Goverde, R. M. P. (2018). Capacity assessment in railway networks. *Handbook of Optimization in the Railway Industry*, 25-45. Springer International Publishing.
17. Kozachenko, D., Skalozub, V., Gera, B., Hermaniuk, Yu., Korobiova, R., & Gorbova, A. (2019). A model of transit freight distribution on a railway network. *Transport Problems, 14*(3), 17-26. https://doi.org/10.20858/tp.2019.14.3.2.
18. Kozachenko, D., Vernigora, R., Kuznetsov, V., Lohvinova, N., Rustamov, R., & Papahov, A. (2018). Resource-Saving Technologies of Railway Transportation of Grain Freights for Export. *Archives of Transport*, *45*(1), 63-74. https://doi.org/10.5604/01.3001.0012.0944.
19. Zitricky, V., Cerna, L., & Abramovic, B. (2017). The Proposal for the Allocation of Capacity for International Railway Transport. *Procedia Engineering*, *192*, 994-999. https://doi.org/10.1016/j.proeng.2017.06.171.
20. Naumov, V. (2012). Definition of the optimal strategies of transportation market participators. *Transport Problems, 7*(1), 43-52.
21. Naumov, V., Taran, I., Litvinova, Z., & Bauer, M. (2020). Optimizing resources of multimodal transport terminal for material flow service. *Sustainability (Switzerland)*, *12*(16), 6545. https://doi.org/10.3390/su12166545.

Удосконалення логістики перевезень продукції видобувної промисловості в умовах обмеження пропускної спроможності залізниць

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Мета. Удосконалення методів розподілу вантажопотоків на залізничній мережі в умовах обмеження пропускної спроможності.

Методика. Використані методи теорії експлуатації залізниць і дослідження операцій. Задача розподілу вантажопотоків на залізничній мережі вирішена як багатопродуктова (взаємозамінні вантажі) транспортна задача лінійного програмування з обмеженнями пропускної спроможності в мережній формі. Середня вартість перевезення вантажів визначена методами теорії ймовірностей.

Результати. У ході дослідження удосконалені методи розподілу вантажопотоків на залізничній мережі. Запропонований підхід до формалізації задачі дозволяє враховувати наявність різних вантажів, що пред'являються до перевезення, обмеження пропускної спроможності окремих ділянок залізничної мережі, а також нелінійний характер залежності між обсягами й вартістю перевезення. Для забезпечення вимоги рівноправності доступу вантажовідправників до послуг громадського перевізника удосконалена методика розрахунку вартості перевезення вантажів окремого відправника.

Наукова новизна. Полягає в удосконаленні методів розподілу вантажопотоків на залізничній мережі й тарифікації послуг на перевезення вантажів в умовах обмеження пропускної спроможності окремих ділянок.

Практична значимість. Підприємства видобувної промисловості формують стійкі вантажопотоки. Основними логістичними задачами при цьому є забезпечення перевезення заданого обсягу вантажу та зниження вартості транспортних послуг. Використання запропонованих у роботі математичних методів оптимізації дозволяє отримувати більш якісні рішення в порівнянні з методом техніко-економічного порівняння варіантів, що забезпечує загальне зниження витрат на перевезення вантажів. Удосконалений метод тарифікації перевезень дозволяє обґрунтовано розподілити між відправниками вантажів економію від скорочення витрат на перевезення і, за рахунок цього, знизити їх логістичні витрати.

Ключові слова: *залізничний транспорт, перевезення вантажів, планування перевезень, транспортна задача*

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