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Analysis of Competitiveness of Small Ports of the Azov-Black Sea Basin in Multimodal Transportation: Technological Aspects, Transportation Problem Optimisation




Maxim V. KOLESNIKOV **Victor A. BOGACHEV** **Vyacheslav M. ZADOROZHNIY** **Maxim V. BAKALOV**

Maxim V. Kolesnikov [1], ***Victor A. Bogachev*** [2],
Vyacheslav M. Zadorozhniy [3], ***Maxim V. Bakalov*** [4]

Rostov State Transport University, Rostov-on-Don, Russia.
✉ [1] *kmv-d@list.ru.*
✉ [2] *bogachev-va@yandex.ru.*
✉ [3] *zadorozniy91@mail.ru.*
✉ [4] *Maxim_bmw@mail.ru.*

ABSTRACT

A new approach is proposed to the study of functioning of the connecting and transforming link of the multimodal transport and logistics chain, implemented by railway cargo transportation. The methodological basis of the research is classical principles of egalitarianism in the theory of welfare, which allow, based on assessment of the transport and technological infrastructure of the network segment and tariff rates, to build mathematical models that are economically justified, customer-oriented and in demand in management of cargo transportation processes.

An algorithm for solving a multi-criteria and multi-extremal problem of integer linear programming with a set of cost objective functions has been developed in the medium of the analytical computing system. The computational experiment is used as a guiding heuristic tool in finding the optimal level of organisation and economic efficiency of the cargo transportation process. Optimal combinations of distributions of the number of departure routes per loading stations and related plans of transportation to the reloading stations were found with the help of the Pareto criterion. The obtained values of cost indicators provide the participants of the transportation process with the opportunity to choose competitive options in transportation schemes using small port transshipment stations of the Azov-Black Sea basin.

Keywords: *multimodal cargo transportation, cost indicators, optimisation, Pareto criterion, «steps» of the «optimisation ladder», «fields of influence» of loading stations, port transshipment stations.*

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INTRODUCTION

When studying the functioning of railway transport, which is a connecting and transforming link in the logistics chain of multimodal cargo transportation, it is relevant and expedient to develop existing and new approaches to optimise transport and logistics processes to increase their efficiency and save resources.

In general, optimisation in transportation problems is the process of finding the best solution for transportation of goods or passengers [1].

One of the methods for solving optimisation problems related to railway transport is optimisation of train routes and schedules [2–5]. This may include rescheduling trains to increase the number of cargo and passenger trains during peak hours, as well as more even load distribution. These measures make it possible to reduce the downtime of trains at stations and reduce the cost of their operation.

Another method for solving these problems is optimisation of the weight characteristics of trains [6].

The integration of information technologies and digital systems makes it possible to increase the efficiency of railway transport, reduce the cost of its operation and maintenance, and improve the quality of service provided to freight customers [7]. Environmental aspects of cargo transportation should be also considered [8].

Based on a review of works devoted to the analysis of the grain transportation market, we note that considerable attention is paid to the analysis of infrastructure and logistics, including the problems of access to the transport infrastructure, its efficiency and competitiveness [9].

Also, it is possible to find studies on certain aspects of the grain transportation market. For example, some studies analyse the impact of climate change on grain transportation [10], including changing transport routes and increasing grain transportation costs. Other studies focus on the analysis of changes in grain transportation tariffs, including the impact of changes in supply and demand on prices [11].

In general, forecasting of tariffs for operation of cargo wagons is an important tool used by railway companies and their customers in managing transportation costs and effectively planning their activities [12; 13].

Several studies analyse the technological aspects of grain transportation, including development of new technologies and innovative solutions to improve transportation efficiency and reduce costs [14; 15].

The objective of the research is to develop new approaches to optimisation of transportation and logistics processes to increase their efficiency and save resources.

The methodology of the research is based on classical principles of egalitarianism in the theory of welfare, which allow, based on assessment of the transport and technological infrastructure of the rail network segment and tariff rates, to build mathematical models that are economically justified, customer-oriented and in demand regarding management of cargo transportation processes.

RESULTS

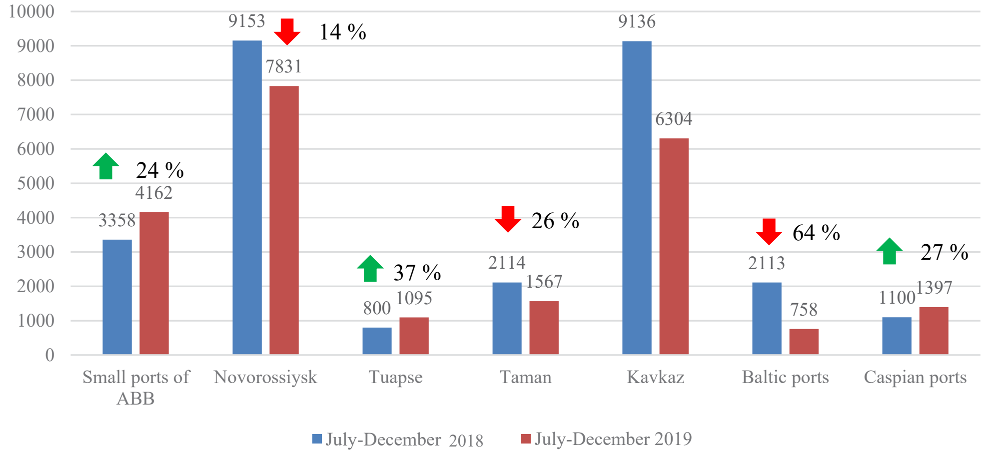
1. Analysis of the Grain Transportation Market

The grain transportation market plays a very significant role in the global economy. In recent years, grain exports from the Russian Federation have been characterised by significant growth (albeit subject to fluctuations). Almost 90 % of grain passes through seaports and almost 81 % – through the ports of the Azov-Black Sea basin (ABB). It should be noted that in July–December 2019, shipments in the ports of the Baltic Sea, as well as in such ABB ports as Kavkaz and Taman, significantly decreased. At the same time, there was an increase in shipments in the port of Tuapse (+37 %), in small ports of ABB (+24 %), as well as in the ports of the Caspian Sea (+27 %). Data on the main directions of Russian grain exports are shown in Pic.1.

In the transport system that provides multimodal transportation of grain in the south of Russia, we will single out the following key components: deep-water ports of Novorossiysk, Taman and Tuapse (allowing to receive ships of Handysize, Suezmax, Panamax standard sizes); small ports of the Sea of Azov; river ports of the Volga and Don.

2. Statement of the Problem and Mathematical Model of the Transforming Link of the Logistics System

The general methodology of the research is based on egalitarian principles of welfare theory [16]. We approach the solution of transportation and logistics problems from the standpoint of



Pic. 1. Main directions of export of grain cargoes. Source: data of Rusagrotrans [rusagrotrans.ru'upload/Русагромранс ГЗА 2020.pdf. Last accessed: 15.01.2023].

one of the basic rules of egalitarianism which is the principle of unanimity in relation to all considered participants in the transportation process (following the terminology of [16], we call them agents). For multimodal transportation systems, coordination of actions of cooperating agents, as well as the level of mutual business trust, are of particular importance. Therefore, in each link of the logistics system, implementation of the interests of any agent should not occur through direct or indirect infringement on the interests of other agents.

The developed methodology for optimised modelling of the process of cargo transportation within the segment of transport network is not directly related to game theory (as is known, this theory of mathematical models is devoted to finding optimal solutions in conflict conditions [17]). We do not consider the strategies of players, and their relationships do not seem to be antagonistic, since the tool for optimising distribution of cargo flows, one way or another, is the Pareto criterion.

Let's move on to the statement of the problem, which considers the key transformative link of the multimodal logistics system, represented by railway cargo transportation. There are m loading stations and n port reloading stations. At each loading station, departure trains are assembled with some cargo. At the same time, the price of cargo at the stations is different. The transshipment stations are such that n_1 of them are deep water ports and n_2 are small ports ($n_1+n_2=n$). Regarding loading stations, it will be necessary to perform mathematical and organisational constructs.

Let B be a given positive integer. Let's introduce a set D, whose elements are all sorts of ordered sets $(a_i)_{i=1}^m$ where a_i are non-negative integers satisfying the condition:

$$\sum_{i=1}^{m} a_i = B \,. \qquad (1)$$

The set D is a subset of the hyperplane defined in the space R^m by the equation (1), whose points have non-negative integer coordinates. From the point of view of combinatorics, each element of the set D can be represented as an arrangement of B indistinguishable objects in m cells. By virtue of the well-known formula [18], we obtain that the number of elements D is equal to:

$$C_{B+m-1}^{m-1} = \frac{(B+m-1)!}{B!(m-1)!} \,. \qquad (2)$$

It can be seen from the right side of the equation (2) how quickly the values C_{B+m-1}^{m-1} increase with increasing values of each of the parameters m and B.

Let us return to the link of the logistics chain represented by railway cargo transportation, assuming that the next (also transformative link) is implemented by sea transport. In this situation, the ordered sets $(a_i)_{i=1}^m \in D$ introduced above represent all possible options for distributing the number a_i of departing trains over m loading stations. These routes are sent to the address of a single or any of the transshipment stations and in total ensure the formation of a complete ship lot with a given volume B.

Further, we will consider the set D, first, in connection with the set of n_2 transshipment stations related to small ports. We introduce two cost indicators that characterise the process of cargo transportation directly or indirectly and allow us to assess the corresponding economic feasibility.

Let p_i be the cost of the cargo that fills the train sent from the i-th loading station $i = 1, 2, \ldots, m$. For each distribution $(a_i)_{i=1}^m \in D$ of the number of trains over m loading stations, we put:

$$P = \sum_{i=1}^{m} p_i a_i \ . \tag{3}$$

The values of the objective function P represent the cost of the entire cargo, which, when the dispatched trains are distributed $(a_i)_{i=1}^m$ among the loading stations, will be transported to the address of some station (or any stations) of transshipment. The introduction of the indicator P is due to the fact that the price of cargo located at different loading stations is different. The objective function (3) represents an «external» (in relation to the business process of cargo transportation) commercial indicator, through which the logistical content of a transportation-type task is developed, first, in relation to the client.

Let us now introduce a set of indicators guided by some considerations and designed to single out one or another of transshipment stations under consideration. These indicators are analogues of the objective function in the classical transportation problem and have the form:

$$C_j = \sum_{i=1}^{m} c_{ij} a_i \ . \tag{4}$$

Here c_{ij} is the cost of transportation of one departing train in the section between the i-th loading station $(i = 1, 2, \ldots, m)$ and the j-th reloading station in a multimodal transportation and logistics chain $(j = 1, 2, \ldots, n)$.

The task of this research is to build (within the specified indicators) an optimisation model of the transforming link of the logistics system, as well as to develop an algorithm for solving the corresponding multi-purpose and multi-extremal problem. The model has a complex character and is represented by interconnected «external» and «internal» parts. The «external» part of the model corresponds to the optimisation problem of finding distributions $(a_i)_{i=1}^m$ of departing trains over loading stations, at which objective function (3) reaches a minimum. The «internal» part of the model corresponds to an optimisation problem (derived from the previous one), in which for each distribution $(a_i)_{i=1}^m$ (varied in the «external» part of the model) transportation plans are found that provide the minimum value of the total cost of transportation (with objective functions (4)) to n_2 transshipment stations (let us recall that the transshipment stations considered in the aggregate n_2 constitute a multimodal transport hub with small ports). Multi-objective optimisation is based on the Pareto criterion, through various forms of which the interests of the agents under consideration are considered.

In accordance with the above, we introduce transportation plans (x_{ij}), where x_{ij} are the numbers of trains sent from the i-th loading station to the address of the j-th reloading station, which must satisfy the equalities:

$$\sum_{j=1}^{n_2} x_{ij} = a_i \quad (i = 1, 2, \ldots, m) \ . \tag{5}$$

Let us recall that the numbers a_i satisfy the condition (1).

3. The Relevance of the Project of Application Project of the Developed Methodology and Project's Features

The developed methodology has for an object of application the transport and technological system (TTS) of the segment of the rail network of the North Caucasian Railway (NCR), adjacent to deep-water ports on the Black Sea coast and small ports in the Taganrog Bay. Due to the intensive exploitation of railway and road approaches to deep-water ports, it seems very relevant to develop alternative options for transformative links of logistics chains, which under the conditions under consideration may turn out to be competitive.

For the numerical implementation of the optimisation model constructed in the article, we will proceed from the following assumptions:

- Grain loading stations are Timashevskaya (1), Apollonskaya (2), Zernograd (3), Salsk (4), Tatsinskaya (5) and Remontnaya (6); port stations are Taman (1), Novorossiysk (2), Tuapse (3), Eisk (4), Taganrog (5) and Azov (6).
- A block train is formed on average of 50 cars with a carrying capacity of 64 tons.
- Cargo ships (of the Panamax type) with a deadweight of up to 80000 tons can call at deep-water ports year-round.

Thus, exactly B = 25 trains are required to fully load one ship lot.

Table 1

Cost characteristics of grain cargo traffic [performed by the authors]

No.	Loading station	Grain price at loading stations, mln rub./route	Cost of transportation, mln rub./train					
			Taman 1	Novorossysk 2	Tuapse 3	Eisk 4	Taganrog 5	Azov 6
1	Timashevskaya 1	46,20	1,39	1,28	1,39	1,28	1,60	1,44
2	Apollonskaya 2	43,84	2,45	2,37	2,04	2,66	2,45	2,37
3	Zernograd 3	45,12	2,05	1,98	2,12	1,44	1,23	1,05
4	Salsk 4	49,60	2,05	1,89	1,97	1,74	1,55	1,39
5	Tatsinskaya 5	43,84	2,57	2,45	2,56	1,89	1,74	1,60
6	Remontnaya 6	45,12	2,45	2,37	2,36	2,12	1,89	1,82

It is to note that the allowable deadweight policy may change over time and depending on many factors (port depth and condition, types of ships, government regulations and regulatory guidelines). Considering the location of the port of Azov, the corresponding railway infrastructure, as well as the rationality of technology of train submission for unloading, we assume that in the situation under consideration, no more than four trains can go to the specified address (from all the indicated loading stations in the aggregate). This constraint corresponds to the fact that sea vessels with a deadweight of up to seven thousand tons can call at the port of Azov (thus, one vessel is practically filled with cargo transported by two trains).

Numerical data that allow performing the corresponding calculations of the optimisation model of cargo transportation are given in Table 1.

4. Preliminary Results

For the software implementation of the optimisation algorithm developed in the article for the logistic modelling of the process of cargo transportation and execution of computational procedures, we turn to the *Maxima (Free Ware)* environment. In this section, we present the results of the corresponding mathematical experiments, which are of a trial nature. Based on considerations of balanced distribution of the number of trains by loading stations, and also taking into account the volume of the ship lot (see Section 3), hereinafter we assume that no more than ten trains with grain can be formed at each loading station.

As already mentioned, the object of application of the developed methodology is the TTS of the North Caucasus Railway range, which includes the port stations of Eisk, Taganrog and Azov (considered in this study in the aggregate). Let's enter the total cost indicator:

$$S=P+C, \quad (6)$$

where $C=C_4+C_5+C_6$ (see (4)).

Let's start by minimising the values of the indicator S, while also observing the changes that occur in other indicators: P, C_4, C_5, C_6, and C. Table 2 shows eight distributions of the number of trains by loading stations, the corresponding transportation plans to the indicated three transshipment stations, as well as the values of the indicators under consideration. We stopped the computation process after the 40-th iteration, guided by several considerations. The main reason for stopping the calculations is positive and lies in the fact that the minimum value of the cost P of the entire transported grain has been reached, which is equal to 1102,4 mln rubles (such a conclusion can be drawn directly from the numerical data contained in Table 1). With constraints imposed on the volume of grain exported from loading stations, the stations that provide the indicated value are Apollonskaya, Tatsinskaya and Zernograd (note that instead of Zernograd station, Remontnaya station can act as the departure station as well). So, (see No. 40 in Table 2), there are ten trains each at Apollonskaya and Tatsinskaya stations, and five trains at Zernograd station.

For the 40-th iteration, the value of the total cost indicator S turned out to be 1149,73 mln rubles. In the process of minimising this indicator, the cost of transportation C increased by more than 9 % (note that the corresponding changes were not monotonous) and reached a value of 47,73 mln rubles. The obtained value of the indicator S is of interest, first, to the client. The value of the indicator C (both in terms of increasing and decreasing the cost of transportation) is also of interest to the owner of

Table 2

Distribution of trains, transportation plans and value of indicators P, C_4, C_5, C_6, C and S [performed by the authors]

No.	Port/ Loading station[1]	Grid of connections of train flows, pcs.						P	C_i	C	S
		Tm1	Ap 2	Zr 3	Sl 4	Tc 5	Rm 6				
1	Total	0	0	0	5	10	10				
	Ek 4	0	0	0	0	0	0	1137,6	0	43,41	1181,01
	Tg 5	0	0	0	1	10	10		37,85		
	Az 6	0	0	0	4	0	0		5,56		
2	Total	0	0	1	4	10	10				
	Ek 4	0	0	0	0	0	0	1133,12	0	43,07	1176,19
	Tg 5	0	0	0	1	10	10		37,85		
	Az 6	0	0	1	3	0	0		5,22		
3	Total	0	0	2	3	10	10				
	Ek 4	0	0	0	0	0	0	1128,64	0	42,73	1171,37
	Tg 5	0	0	0	1	10	10		37,85		
	Az 6	0	0	2	2	0	0		4,88		
…	…	…	…	…	…	…	…	…	…	…	…
15	Total	0	3	9	0	10	4				
	Ek 4	0	0	0	0	0	0	1112,64	0	40,21	1152,85
	Tg 5	0	2	5	0	10	4		36,01		
	Az 6	0	0	4	0	0	0		4,2		
16	Total	0	2	10	0	10	3				
	Ek 4	0	0	0	0	0	0	1112,64	0	39,75	1152,39
	Tg 5	0	0	8	0	10	3		32,91		
	Az 6	0	2	2	0	0	0		6,84		
…	…	…	…	…	…	…	…	…	…	…	…
38	Total	0	8	7	0	10	0				
	Ek 4	0	0	0	0	0	0	1104,96	0	44,89	1149,85
	Tg 5	0	8	3	0	10	0		40,69		
	Az 6	0	0	4	0	0	0		4,2		
39	Total	0	9	4	0	10	0				
	Ek 4	0	0	0	0	0	0	1103,68	0	46,11	1149,79
	Tg 5	0	9	0	0	10	0		41,91		
	Az 6	0	0	4	0	0	0		4,2		
40	Total	0	10	5	0	10	0				
	Ek 4	0	0	0	0	0	0	1102,4	0	47,33	1149,73
	Tg 5	0	10	1	0	10	0		43,13		
	Az 6	0	0	4	0	0	0		4,2		

the infrastructure and the carrier (for example, based on considerations of the competitiveness of railway transport in relation to road transport). Note that in all iterations, Eisk transshipment station turned out to be devoid of trains arriving at it, which also allows for different interpretations in relation to agents.

To obtain preliminary results, we will also consider the process of minimising the values of the cost indicator C, assuming that the values of the indicator P do not change and remain equal to the minimum value of 1102,4 (million rubles). (Note that it was possible to minimise the values of the exponent S). The corresponding results are shown in Table 3.

The same values were obtained as in the previous experiment (compare the last rows in Tables 2 and 3). Thus, for agents whose interests are primarily focused on minimising the total cost indicator S, the given results (within the limits set) seem to be unimprovable.

5. Auxiliary Results

Another reason for stopping the process of obtaining preliminary results is the large number of calculations performed when solving the optimisation problems under consideration. It

[1] Here and after the stations will be indicated by abridged names and numbers according to the Table 1 and the text. – *Ed. note*

Table 3

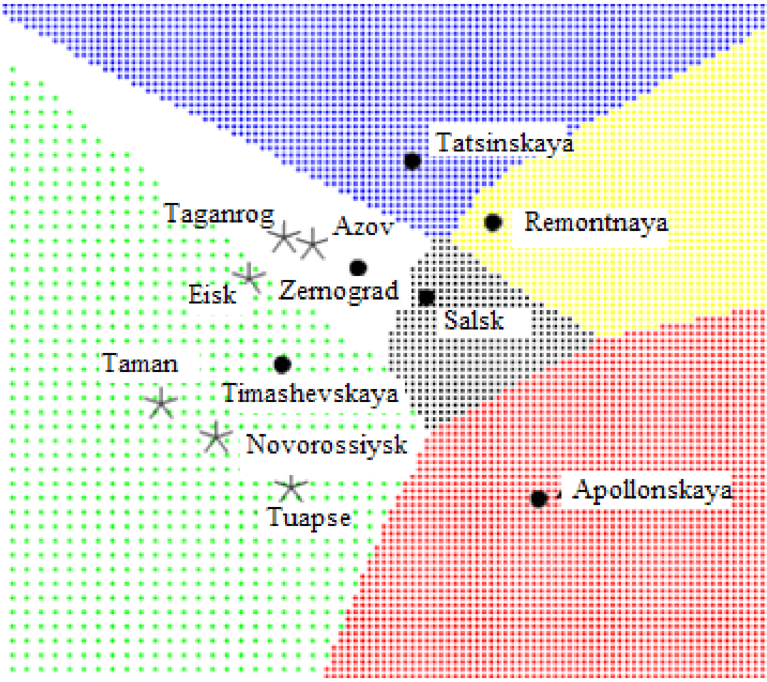
Distribution of the number of trains, transportation plans and values of indicators *P*, C_4, C_5, C_6, *C* and *S* [performed by the authors]

No.	Port/ Loading station	Grid of connections of train flows, pcs						P	C_i	C	S
		Тм1	Ар 2	Зр 3	Сл 4	Тц 5	Рм 6				
1	Total	0	10	0	0	10	5				
	Ek 4	0	0	0	0	0	0	1102,4	0	51,35	1153,75
	Tg 5	0	10	0	0	10	5		51,35		
	Az 6	0	0	0	0	0	0		0		
2	Total	0	10	0	0	10	5				
	Ek 4	0	0	0	0	0	0	1102,4	0	51,28	1153,68
	Tg 5	0	10	0	0	10	4		49,46		
	Az 6	0	0	0	0	0	1		1,82		
3	Total	0	10	0	0	10	5				
	Ek 4	0	0	0	0	0	0	1102,4	0	51,21	1153,61
	Tg 5	0	10	0	0	10	3		47,57		
	Az 6	0	0	0	0	0	2		3,64		
	…	…	…	…	…	…	…	…	…	…	…
19	Total	0	10	1	0	10	4				
	Ek 4	0	0	0	0	0	0	1102,4	0	50,09	1152,49
	Tg 5	0	10	0	0	7	4		44,24		
	Az 6	0	0	1	0	3	0		5,85		
20	Total	0	10	2	0	10	3				
	Ek 4	0	0	0	0	0	0	1102,4	0	39,75	1152,43
	Tg 5	0	10	2	0	10	3				
	Az 6	0	0	0	0	0	0				
…	…	…	…	…	…	…	…	…	…	…	…
60	Total	0	10	5	0	10	0				
	Ek 4	0	0	0	0	0	0	1102,4	0	47,41	1149,81
	Tg 5	0	10	3	0	8	0		42,11		
	Az 6	0	0	2	0	2	0		5,3		
61	Total	0	10	5	0	10	0				
	Ek 4	0	0	0	0	0	0	1102,4	0	47,37	1149,77
	Tg 5	0	10	2	0	9	0		42,62		
	Az 6	0	0	3	0	1	0		4,75		
62	Total	0	10	5	0	10	0				
	Ek 4	0	0	0	0	0	0	1102,4	0	47,33	1149,73
	Tg 5	0	10	1	0	10	0		43,13		
	Az 6	0	0	4	0	0	0		4,2		

follows from formula (5) that the number of admissible transportation plans (x_{ij}) in the considered project is estimated from below by the number:

$$C^{m-1}_{B+m-1} \bullet C^{n_2-1}_{B+n_2-1} = \frac{30! \bullet 27!}{(25!)^2 \bullet 5! \bullet 2!} = 50019606. \qquad (7)$$

To find additional and reasonable constraints on the sets of admissible transportation plans, we turn to *the geometric Euclidean model (GEM)* developed earlier by the authors for the territorial oligopolistic cargo market created by loading stations. The method of economic-geographical delimitation of the areas of influence of loading



Pic. 2. A picture of the territorial grain transportation market [performed by the authors].

stations, which makes it possible to construct this model, is described in detail in [19–21]. Only the corresponding results are presented here, which were obtained based on (found using the least squares method) expressions for the dependence of the cost *c* of cargo transportation for the loading stations under consideration (see Table 4).

In this case, the lines delimiting the «fields of influence» of loading stations in duopolistic situations are the branches of hyperbolas (parts of these branches are depicted by the *Maxima* analytical computing system in Pic. 2). The «area of influence» of Timashevskaya station (1) included the port stations Taman, Novorossiysk, Tuapse and Eisk, and the «area of influence» of Zernograd station included the stations of Taganrog and Azov. Thus, none of the considered port stations fell into the «field of influence» of other four loading stations. Since the costs of start-end operations at loading stations are pairwise different (see Table 4), these results do not follow from simple geographical considerations.

Note that the use of methods of various mathematical nature in applied research makes it possible to increase the degree of reliability of the results obtained. In this case, it is often possible to significantly reduce the number of computational procedures performed when

Table 4

Expressions of dependence of transportation cost [performed by the authors]

1	Timashevskaya	c = 0,002l + 0,819
2	Apollonskaya	c = 0,002l + 0,912
3	Zernograd	c = 0,002l + 0,830
4	Salsk	c = 0,002l + 0,892
5	Tatsinskaya	c = 0,002l + 0,833
6	Remontnaya	c = 0,002l + 0,959

solving the corresponding optimisation problems. Based on the *GEM* of the territorial cargo market, we impose the following constraints on the set of admissible transportation plans. We will assume that no more than three trains can be sent to Eisk port station from all loading stations, except for Timashevskaya (1). In addition, more than three routes to Taganrog station cannot be sent from the specified loading station.

6. Discussion

Let's move on to the multi-criteria optimisation of the process of cargo transportation to the transshipment stations Eisk, Taganrog and Azov, which are considered together. Optimisation will be carried out on the basis of the egalitarian approach in welfare theory [16] within the framework of the cost indicators *P* and *C* introduced in Section 2. The tool that implements the unanimity principle is the Pareto criterion.

Table 5

Distribution of the number of routes, transportation plans and values of indicators *P*, C_4, C_5, C_6, *C* and *S* [performed by the authors]

No.	Port/ Loading station	Grid of connections of train flows, pcs						P	$\mathbf{C}_i$	C	S
		Tm1	Ap2	Zr3	Sl4	Tc5	Rm6				
1	Total	0	10	0	5	0	10				
	Ek 4	0	0	0	0	0	0	1137,6	0	50,83	1188,43
	Tg 5	0	6	0	5	0	10		41,35		
	Az 6	0	4	0	0	0	0		9,48		
2	Total	0	10	0	5	0	10				
	Ek 4	0	0	0	0	0	0	1137,6	0	50,75	1188,35
	Tg 5	0	7	0	4	0	10		42,25		
	Az 6	0	3	0	1	0	0		8,5		
3	Total	0	10	0	5	0	10				
	Ek 4	0	0	0	0	0	0	1137,6	0	50,67	1188,27
	Tg 5	0	8	0	3	0	10		43,15		
	Az 6	0	2	0	2	0	0		7,52		
…	…	…	…	…	…	…	…	…	…	…	…
52	Total	0	9	9	0	1	6				
	Ek 4	0	0	0	0	0	0	1115,2	0	45,48	1160,68
	Tg 5	0	9	5	0	1	6		41,28		
	Az 6	0	0	4	0	0	0		4,2		
53	Total	0	10	10	0	1	4				
	Ek 4	0	0	0	0	0	0	1113,92	0	45,48	1159,4
	Tg 5	0	9	7	0	1	4		39,96		
	Az 6	0	1	3	0	0	0		5,52		
…	…	…	…	…	…	…	…	…	…	…	…
94	Total	0	5	10	0	10	0				
	Ek 4	0	0	0	0	0	0	1108,8	0	41,43	1150,23
	Tg 5	0	3	8	0	10	0		34,59		
	Az 6	0	2	2	0	0	0		6,84		
95	Total	0	5	10	0	10	0				
	Ek 4	0	0	0	0	0	0	1108,8	0	41,33	1150,13
	Tg 5	0	4	7	0	10	0		35,81		
	Az 6	0	1	3	0	0	0		5,52		
96	Total	0	5	10	0	10	0				
	Ek 4	0	0	0	0	0	0	1108,8	0	41,23	1150,03
	Tg 5	0	5	6	0	10	0		37,03		
	Az 6	0	0	4	0	0	0		4,2		

To each distribution of the number of trains $(a_i)_{i=1}^{m} \in D$ over *m* loading stations and to each related plan of transportation (x_{ij}) to the transshipment stations under consideration, we assign a vector $\{P, C\}$, called the utility vector. An optimal combination of distribution of the number of trains and a transportation plan is such a combination of $(a_i^*)_{i=1}^{m}$ and $(x_{ij}^{\ *})$ with the utility vector $\{P^*, C^*\}$, that there is no combination of $(a_i)_{i=1}^{m}$ and (x_{ij}), the coordinates of the utility vector $\{P, C\}$ that satisfy the condition ($P<P^*$, $C \le C^*$) or a condition ($P \le P$ and $C<C^*$).

From the sentential link expression:

$$\left(P < P^* \wedge C \le C^*\right) \vee \left(P \le P^* \wedge C < C^*\right), \qquad (8)$$

it follows that in the process of optimisation there is no loss of utility for any of the agents interested in minimising the indicators *P* and *C*.

Table 5 shows eight sets of numerical data from 96 «steps» found by *Maxima* and making up the corresponding «optimisation ladder».

Table 6

Distribution of the number of trains and values of indicators P, C_1 and $P+C_1$ [performed by the authors]

No.	Number of trains formed at loading stations						P	C_1	S
	Tm1	Ap2	Zr3	Sl4	Tc5	Rm6			
1	0	0	0	5	10	10	1137,6	60,45	1198,05
2	0	0	1	4	10	10	1133,12	60,45	1193,57
3	0	0	2	3	10	10	1125,64	60,45	1189,09
…	…	…	…	…	…		…	…	…
37	2	10	10	0	2	1	1114,8	55,37	1170,17
38	3	6	9	0	7	0	1114,6	55,31	1169,91
…	…	…	…	…	…		…	…	…
48	6	10	3	0	6	0	1114,0	54,41	1168,41
49	7	9	1	0	8	0	1113,8	54,39	1168,19
50	7	10	1	0	7	0	1113,8	54,27	1168,07

For the optimal combination of distribution of the number of trains by loading stations and the transportation plan, it turns out (see No. 96 in Table 5) that five trains should be formed at Apollonskaya station, and ten trains at each Zernograd and Tatsinskaya stations. At the same time, the value of the indicator S turns out to be equal to 1150,03 mln rubles, that is, it practically coincides with the value of 1149,73 mln rubles obtained in Section 4. However, the value of indicator C turns out to be 41,23 mln rubles, that is, 6,1 mln rubles less than in the previous case (the difference is almost 13 %).

So, in the optimal combination, from the point of view of the client, the indicators are not inferior to the previous ones, but in relation to the carrier, the owner of the transport infrastructure and the operator company, they may turn out to be more preferable.

For comparison, let's consider the results of optimisation of cargo transportation performed to Taman deep-sea transshipment station. Here we use the Pareto criterion with indicators P and C_1. Table 6 shows eight sets of numerical data from 50 «steps» that make up the corresponding «optimisation ladder».

For the optimal distribution of the number of trains by loading stations (note that it differs significantly from the distributions obtained for the aggregate of small ports), the following values were obtained: P=1113,8 mln rubles, C_1=54,27 mln rubles and $S=P+C_1$=1168,07 mln rubles. In this case, the cost of transportation is 13,04 mln rubles more than for transportation to small ports (the difference is almost 32 %).

CONCLUSION

An approach based on egalitarian principles of the theory of welfare has been developed in studying the functioning of the key connecting and transforming link in the logistics system, which is cargo transportation by rail. The mathematical model of the transportation process, considered within the framework of a set of cost indicators, is a multicriteria and multiextremal problem of integer linear programming. In view of the special importance for multimodal cargo transportation systems of coordinating the actions of cooperating agents and the level of their business trust, implementation of the interests of any agent should not occur by infringing on the interests of others.

Pareto-optimal combinations of distributions of the number of trains by loading stations and related plans of cargo transportation to the reloading stations are found. The corresponding values of cost indicators provide agents with the opportunity to choose alternative options in transportation schemes in terms of competitiveness of small near-port transshipment stations in relation to deep-sea stations.

The program implementation of the optimisation algorithm for the functioning of the considered link of the logistics system is made in the environment of the analytical computing system. Appeal to computational experiments creates opportunities for purposeful operation with the values of objective functions and constraints in a transportation-type problem to identify the optimal level of organisation and economic efficiency of the transportation process.

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Information about the authors:

***Kolesnikov, Maxim V.,** D.Sc. (Eng), Professor at the Department of Economics and Management of Rostov State Transport University, Rostov-on-Don, Russia, kmv-d@list.ru.*

***Bogachev, Victor A.,** Ph.D. (Physics and Mathematics), Associate Professor, Associate Professor at the Department of Higher Mathematics of Rostov State Transport University, Rostov-on-Don, Russia, bogachev-va@yandex.ru.*

***Zadorozhniy, Vyacheslav M.,** Ph.D. (Eng), Associate Professor, Associate Professor at the Department of Stations and Cargo Operations of Rostov State Transport University, Rostov-on-Don, Russia, adorozniy91@mail.ru.*

***Bakalov, Maxim V.,** Ph.D. (Eng), Associate Professor at the Department of Operations Management of Rostov State Transport University, Rostov-on-Don, Russia, Maxim_bmw@mail.ru.*

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