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Economic and mathematical modeling of operating costs in sea freight transportation under uncertainty

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Abstract. The formulation of the problem of distribution of the fleet along the lines as a problem of linear programming assumes the complete certainty of the volume of traffic for the planned period on each cargo flow, the certainty of the availability of the fleet and the planned indicators of the use of the fleet. Meanwhile, due to a number of reasons, it is not always possible to determine the amount of cargo flows for navigation with the required degree of reliability. An analysis of the reporting data of the transport fleet in terms of cargo flows showed that the planned applications of shippers are often implemented with deviations of 4-15% in the direction of excess and decrease [4]. Although these changes can be largely taken into account in the operational regulation of the fleet, in some cases it is advisable to take into account possible fluctuations in traffic volumes in the economic and mathematical model of the fleet arrangement at the stage of developing the annual schedule scheme. The size of fluctuations in traffic volumes is of a different nature and varies depending on cargo flows. In this regard, to solve the problem of fleet placement in the presence of a significant fluctuation in traffic volumes, it is advisable to consider the use of parametric programming. In the article based on statistical data 20013-2021, analysed and estimated costs per 1 ton-kilometre cargo turnover for the sea transport fleet. An economic-mathematical model was built here and the scheduling problem was solved to minimize operational costs of transportation under conditions of uncertainty on two operational lines of the Transport fleet [5].

Keywords*: *fleet; ship; economic-mathematical model; cargo flow; carrying capacity; inequality; optimal plan; parameter

1. INTRODUCTION

For the development of transportation in shipping companies, various types of fleet are currently used: self-propelled cargo ships, pushed sectional and barge trains with permanent traction and tonnage fixing, self-propelled cargo ships with attachments, unsecured barges. Typically, each type of fleet includes several types of ships.

Various types of vessels and convoys are highly versatile and can be used on a large number of cargo lines. At the same time, the resources of each type of vessels are limited, as a result, the assignment of any type of vessels to a given area of work predetermines the scope of use of the remaining types of vessels and trains and, consequently, the layout and indicators of the use of the entire fleet fleet.

When substantiating the technological process of the operation of the fleet and ports, one of the main issues is to find the most advantageous arrangement of the indicated types of fleet and types of vessels according to the work areas in order to achieve the best indicators for the use of the entire fleet: total carrying capacity, average cost of transportation, the highest profit from transportation. A distinctive feature of this task is the possibility of compiling a very large number of alternative options for the placement of various types of vessels in the work area, characterized by the value of the indicated indicators. From this large number of possible options for using the fleet, it is necessary to find the most profitable one [2].

2. CONSTELLATION PROBLEM WITH INDETERMINATIVE VOLUMES OF TRANSPORTATION IN THE CASPIAN FLEET

Let us consider the distribution problem under the condition that the volumes of transportation Q_j on the lines are not fixed exactly, but are set only in certain ranges:

$$Q_j^0 \leq Q_j \leq Q_j^0 + \Delta Q_j^0 \ \ j = 1, 2, \dots, n)$$

$$Q_j^0 \leq Q_j \leq Q_j^0 + \Delta Q_j^0 \quad (j = 1, 2, \dots, n)$$

.

where, the minimum volumes Q_j^0 and their possible increments ΔQ_j^0 are given. Introducing the parameter t changing in the interval $0 \leq t \leq 1$, we can represent the traffic volumes on the lines as linear functions of the parameter t:

$$Q_j = Q_j^0 + t\Delta Q_j^0 \quad (j = 1, 2, \dots, n)$$

The constellation problem for the minimum cost in this case will be expressed as follows:

$$Z(x) = \sum_{i=1}^{m} \sum_{j=1}^{n} R_{ij} * x_{ij} \to min;$$

$$\sum_{j=1}^{n} x_{ij} \leq 1 \ \ (i = 1, 2, \dots, m)$$

$$\sum_{i=1}^{m} p_{ij} x_{ij} = Q_j^0 + t\Delta Q_j^0 \ \ (j = 1, 2, \dots, n)$$

where, P_{ij} - is the carrying capacity of the i-th vessel on the j - th line (for the entire operational period); x_{ij} - is the planned share of the operational period for the i - th vessel on the j - th line; R_{ij} - is the operating expense (for the entire period) for the i -th vessel on the j - th line [3].

We obtain, therefore, in this case the second particular problem of linear parametric programming, when only the right parts of the constraints depend on the parameter. Accordingly, using the principle of duality, this problem can be reduced to the first particular problem of linear parametric programming. It is also possible to solve this problem without passing to the dual problem.

All this can be explained by the transport line of two cargo ships belonging to the Sea Transport Fleet Closed Joint Stock Company "Azerbaijan Caspian Shipping Company" in the directions of Baku-Aktau and Baku-Turkmanbashi [3]. It should be noted that in 2013-2016 and in 2019-2021, a significant decrease in cargo traffic in the directions of Makhchkala-Baku-Dyubendi-Sangachal, Turkmenbashi-Makhachkala, Turkmenbashi-Okarem caused a decrease in cargo traffic in the Transport Fleet. This can be seen more clearly in the graph below.

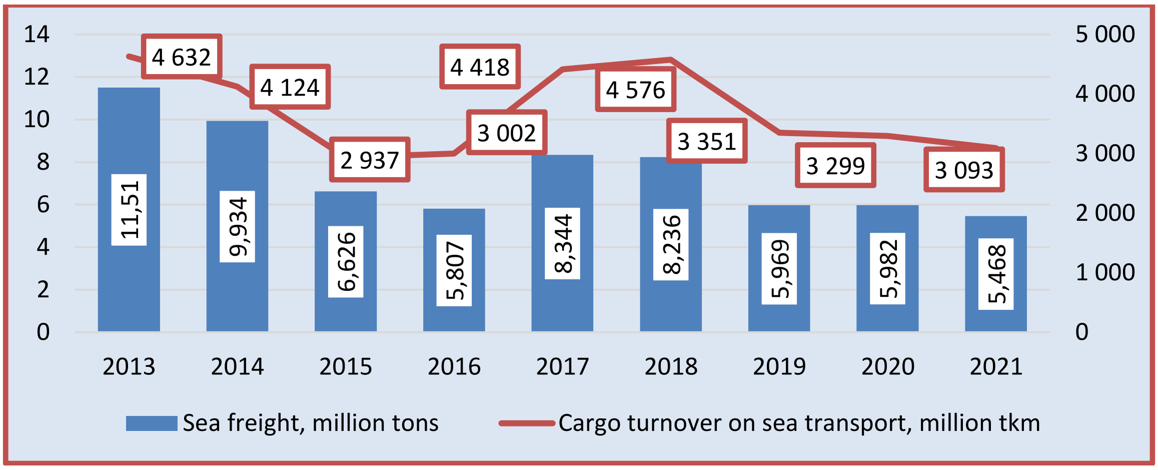

Fig. 2.1. The volume of cargo transportation and cargo turnover in sea transport for 2013-2021

Source: Sourced from (5).

As can be seen from the graph, compared to 2013, the decrease in cargo transportation by sea in the Republic of Azerbaijan compared to 2013 led to a decrease in cargo turnover. In 2021, freight traffic decreased by 8.5% compared to the previous year and by 52.4% compared to 2013. Similarly, cargo turnover decreased by 6.2% compared to the previous year and by 33.2% compared to 2013 and amounted to 3,093 million tkm. Despite the decrease in cargo turnover, the operating costs of ships increased with increasing dynamics. These figures can be seen more clearly in the chart below.

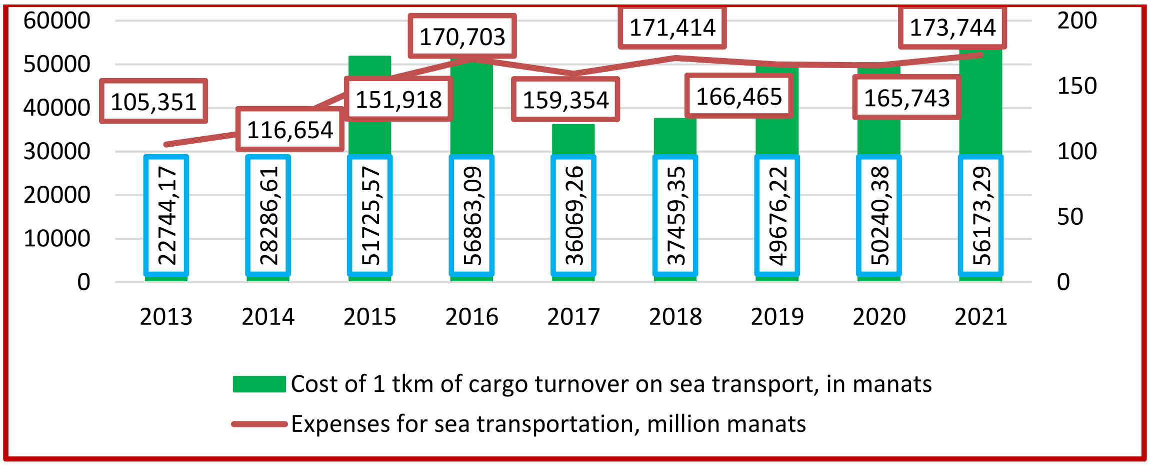

Fig. 2.2. Costs for the transportation of goods by sea and the amount of costs per 1 ton km of cargo turnover
Source: Sourced from (5).

As can be seen from the graph, despite the decrease in cargo transportation and cargo turnover in 2013-2021, cargo transportation expenses increased in 2021 and amounted to 173,744 million manats in 2021. This is 4.8% more than in 2020, and 64.9% or 68.393 million manats more than in 2013. The increase in costs for the transportation of goods by ships, despite the decrease in cargo transportation, led to an increase in the cost of 1 tkm of cargo turnover. Thus, in 2021, the cost of 1 ton-kilometer freight turnover increased by 5932.91 manats compared to the previous year and amounted to 56173.3 manats. Studies show that all this occurred in the conditions of uncertainty of the volume of cargo transportation. From this point of view, it is very important to reduce the operating expenses on the line of operating ships. The following table shows the carrying capacity and operating costs of two cargo ships on the Baku-Aktau and Baku-Turkmanbashi routes [1].

Tab. 2.1

Carrying Capacity and Operating Costs of Vessels on Operating Lines

Vessel	carrying capacity		Operating costs	
	on line 1	on line 2	on line 1	on line 2
1	100	50	25	30
2	50	100	10	40
Volume of transportation	100-120	20-30	-	-

Source: Compiled according to the Marine Transport Fleet.

Using the parameter t, $0 \leq t \leq 1$, the given traffic volumes will be written as follows: on the first line $100 + 20t$; on the second $20 + 10t$ The mathematical model of the problem will look like:

$Z(x) = 25x_{11} + 30x_{12} + 10x_{21} + 40x_{22} \rightarrow min;$ Dual Variables

$$
\begin{array}{ll}
x_{11} + x_{12} \leq 1 & -u_1 \\
x_{21} + x_{22} \leq 1 & -u_2 \\
100x_{11} + 50x_{21} = 100 + 20t & v_1 \\
50x_{12} + 100x_{22} = 20 + 10t & v_2 \\
x_{ij} \geq 0 \qquad (i, j = 1, 2). &
\end{array}
$$

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Let's move on to the dual problem with dual variables:
$-u_1$, $-u_2$, v_1 , v_2 (potentials!); we get:

$$
\begin{gathered}
Z' = (100 + 20t)v_1 + (20 + 10t)v_2 - u_1 - u_2 \rightarrow max \\
100v_1 - u_1 \leq 25 \\
50v_2 - u_1 \leq 30 \\
50v_1 - u_2 \leq 10 \\
100v_2 - u_2 \leq 40 \\
u_1 \geq 0, u_2 \geq 0
\end{gathered}
$$

The parameter t has moved to the coefficients of the objective function - we have received the first particular problem of linear parametric programming.

The following 4 Jordan tables 2.2-2.5 contain the solution of the problem for t = 0, and the second final line is introduced everywhere - for Z' with variable t/

Tab. 2.2

	$-v_1$	$-v_2$	$-u_1$	$-u_2$	1
$y_1 =$	100	0	-1	0	25
$y_2 =$	0	50	-1	0	30
$y_3 =$	50	0	0	-1	10
$y_4 =$	0	100	0	-1	40
$Z'_{t=0}$	-100	-20	1	1	0
$Z'=$	-100 -20t	-20 -10t	1 0	1 0	0 0

Tab. 2.3

	$-y_3$	$-v_2$	$-u_1$	$-u_2$	1
$y_1 =$	-2	0	-1	2	5
$y_2 =$	0	50	-1	0	30
$v_1 =$	0.02	0	0	-0.02	0.2
$y_4 =$	0	100	0	-1	40
$Z'_{t=0}$	-2	-20	1	-1	20
Z'=	2 0.4t	-20 -10t	1 0	-1 -0.4t	20 4t

Tab. 2.4

	$-\boldsymbol{y_3}$	$-\boldsymbol{y_4}$	$-\boldsymbol{u_1}$	$-\boldsymbol{u_2}$	**1**
$\boldsymbol{y_1} =$	**-2**	**0**	**-1**	**2**	**5**
$\boldsymbol{y_2} =$	**0**	**-0.50**	**-1**	**0.5**	**10**
$\boldsymbol{v_1} =$	**0.02**	**0**	**0**	**-0.02**	**0.20**
$\boldsymbol{v_2} =$	**0**	**0.01**	**0**	**-0.01**	**0.40**
$\boldsymbol{Z'_{t=0}}$	**2**	**0.2**	**1**	**-1.2**	**28**
$\boldsymbol{Z'}$=	**2** **0.4t**	**0.2** **0.1t**	**1** **0**	**-1.2** **-0.5t**	**28** **8t**

Table 2.5

	$-\boldsymbol{y_3}$	$-\boldsymbol{y_4}$	$-\boldsymbol{u_1}$	$-\boldsymbol{y_1}$	**1**
$\boldsymbol{u_2} =$	**-1**	**0**	**-0.5**	**0.5**	**2.5**
$\boldsymbol{y_2} =$	**0.5**	**-0.50**	**-0.75**	**-0.25**	**8.75**
$\boldsymbol{v_1} =$	**0**	**0**	**-0.01**	**0.01**	**0.25**
$\boldsymbol{v_2} =$	**-0.01**	**0.01**	**-0.005**	**0.005**	**0.425**
$\boldsymbol{Z'_{t=0}}$	**0.8**	**0.2**	**0.4**	**0.6**	**31**
$\boldsymbol{Z'}$=	**0.9** **-0.1t**	**0.2** **0.1t**	**0.4** **-0.25t**	**0.6** **0.25t**	**31** **9.25t**

In the last table 1.4, the optimal design for the dual problem at $t = 0$ has already been reached, since all elements of the penultimate row are positive. This plan will remain optimal if the inequalities expressing the non-negativity of the elements of the last row:

$0.8 - 0.1t \geq 0;$ $\quad$ $0.4 - 0.25t \geq 0$

$0.2 + 0.1\text{t} \geq 0;$ $\quad$ $0.6 + 0.25t \geq 0$

Inequalities 2nd and 4th are satisfied for any $t \geq 0$, and to fulfill the 1st and 3rd inequalities, it is necessary that $t \leq 8$ (1st inequality), $t \leq 1.6$ (3rd inequality). So, in the given interval $0 \leq t \leq 1$, all four inequalities are satisfied, and, consequently, the optimal plan at $t = 0$ remains optimal throughout the given interval (here we have obtained a stable optimal plan).

The elements of the final line of the dual problem give the plan of the original problem; one should only carefully follow the correspondence between the variables of the direct and dual problems (the additional variables of the dual problem correspond to the main variables of the direct problem, and vice versa).

In this case, the match is:

$y_1 \quad y_2 \quad y_3 \quad y_4 \quad u_1 \quad u_2$

$$\begin{array}{cccccc} \downarrow\uparrow & \downarrow\uparrow & \downarrow\uparrow & \downarrow\uparrow & \downarrow\uparrow & \downarrow\uparrow \\ x_{11} & x_{12} & x_{21} & x_{22} & x_{13} & x_{23} \end{array}$$

where x_{13}, x_{23} are additional variables in the 1st and 2nd constraints of the direct problem (which are introduced in the transition from inequalities to the equalities $x_{11}+x_{12}+x_{13}=1$; $x_{21}+x_{22}+x_{23}=1$). Thus, we have (by the final elements of the columns):

$x_{21}=0.8-0.1t$ (column under y_3); $x_{13}=0.4-0.25t$ (column under them u_1);

$x_{22}=0.2+0.1t$ (column under y4); $x_{11}=0.6+0.25t$ (column under y_1).

Further, since $y_2>0$; $u_2>0$, then the corresponding dual variables are equal to zero: $x_{12}=0$, $x_{23}=0$ [4].

Let's write down the received optimum plan in the usual table of the distributive task (tab. 2.6).

25 0.6+0.25t 100	30 50	0 0.4-0.25t 0
25 0.8-0.1t 50	40 0.2+0.1t 100	0 0

We see that the numerical values of the variables in this optimal plan are not strictly fixed, but contain the parameter t $(0<t<1)$, so that they fluctuate in the following ranges:

x_{11} - from 0.6 to 0.85; x_{21} - from 0.8 to 0.7; x_{22} - from 0.2 to 0.3; x_{13} - from 0.4 to 0.15; $x_{12}=x_{23}=0$. This, apparently, is due to the fact that the presented traffic volumes are also set in certain ranges.

3. CONCLUSİON

The use of a parametric formulation of the problem of distributing vessels and trains across work areas requires a slightly larger amount of computational work, but the plan for using the fleet obtained in this case has clear boundaries for the stability of the optimal plan with changes in the volume of traffic on the lines. The main advantage of the parametric formulation of the fleet distribution problem is that in this case it is possible to take into account possible fluctuations in traffic volumes, to obtain a solution that is not of a narrowly deterministic nature.

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