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Optimization of the Enterprise Railcar Fleet Structure for the Transportation of Iron Ore Raw Materials

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Abstract

The paper is devoted to the transportation issues of iron ore raw materials by railway transport. The purpose of the research is determining the number of private cars a mining enterprise should have to transport its products. The research is performed using the methods of the theory of railways operation, economic and mathematical modeling, mathematical statistics and direct methods of minimization. During the research the task for determining the number of private cars of the enterprise is reduced to the stochastic problem of minimizing the modified reduced costs of the enterprise, which are represented by a piecewise nonlinear function of one variable. The originality of the work is related to the fact that it has improved the method for calculating the car fleet of enterprises by taking into account differences in the technology of loading private cars and the involved cars of operator companies. The practical value of the work lies in the fact that the proposed method allows one to reduce the logistics costs of mining enterprises due to a more accurate assessment of the costs associated with the development and operation of the car fleet, as well as the accompanying railway infrastructure of sidings.
KEY WORDS: *railways, ore transportation, railcar fleet, optimization*

1. Introduction

Twenty percent of the world's iron ore reserves are located on the territory of Ukraine. Ukraine ranks first in the world in terms of reserves of iron ore raw materials, and seventh in terms of production volumes. Iron ore is used both by the metallurgical industry of Ukraine and is exported. At the same time, the share of iron ore is about 7% of Ukraine's merchandise exports in monetary terms. Delivery of iron ore raw materials (pellets, iron ore concentrate) from mining sites to sites of processing or transshipment to sea transport is associated with the need to move significant cargo volumes and the main transport mode in Ukraine is rail transport. The share of iron ore in the volume of rail transport in Ukraine is about 20%. Considering the relatively low cost of iron ore raw materials, a significant part of its cost for the end user is associated with logistics costs; therefore, reducing the cost of transporting iron ore raw materials by rail is an important problem for both individual enterprises and the Ukrainian economy as a whole. One of the tasks arising in this case is to determine the size and structure of the car fleet required by a mining enterprise to perform transportation. This article is devoted to solving this problem.

2. Literature Review and Purpose of the Study

The methods of calculating the car fleet required for transportation practically used in railway transport at present are based on the results of a statistical analysis of the use of rolling stock in previous periods. Engineer N. Kulzhynskyi proposed this approach back in 1878. Already at the beginning of the 20th century, there were various formulas linking various indicators of the operational work of railways and the required fleet for its development. As examples of such formulas, the expressions connecting the size of the operating car fleet N with the work of the car fleet (the number of loaded and received loaded cars by the railway division) U, cars, mileage $\sum NS$, car-km and cargo turnover Pl_{cg}, t-km net are given below.

$$N = U\theta; \; N = \frac{\sum NS}{\bar{S}}; \; N = \frac{Pl_{cg}}{\bar{W}_c},$$

where θ – car turnover, day; $\bar{S}$ – average daily car mileage, km/day; $\bar{W}_c$ - average daily car productivity, t-km net/car.

If the assessment of the need for car fleet is carried out in the process of medium-term and long-term planning, then it is necessary to take into account the unevenness of the volume of freight operation in time, as well as the fact that some of the cars are under repair and cannot be used for transportations. The simplest approach to accounting of these factors is associated with the use of multiplying factors. Thus, in [1], it is proposed to determine the car fleet necessary for transportations of goods by the following formula:

$$N = \frac{U_m \theta}{30.4} k_r k_{ir} ,$$

where U_m − the planned volume of loading cars during the month, cars; 30.4 – average number of days in a month, days; k_r – coefficient taking into account the car stay under repair; k_{ir} – loading irregularity coefficient.

Another way of accounting the irregularity of transportations is given in the work [2], where the irregularity of the car turnover value when calculating the operating fleet is taken into account using the coefficient of variation:

$$N = \frac{Q}{p_{st} t_c} \left(1 + CV\right),$$

where t_c – the number of the car turnovers during the planning period; CV − coefficient of variation of the car turnover duration.

It should be noted that the parameters of all the above calculation formulas are random values. Their values can differ significantly from the average ones and change over time. A significant drawback of direct using statistical data on the operation of cars to estimate the number of cars required for transportation in the future is associated with the fact that the management of the existing fleet may not be optimal. This problem is considered in detail in [2], where an element-by-element analysis of the car turnover process during the chemical products transportation is carried out. In the same paper, the reasons for car delays in different service phases are considered and approaches to their minimization are proposed. There is a significant number of works in which the size of the car fleet is established as a result of solving optimization problems for organizing the movement of car traffic volumes in the network [3-10]. The main part of these works is aimed at optimizing the size of the car fleet of carriers and operators.

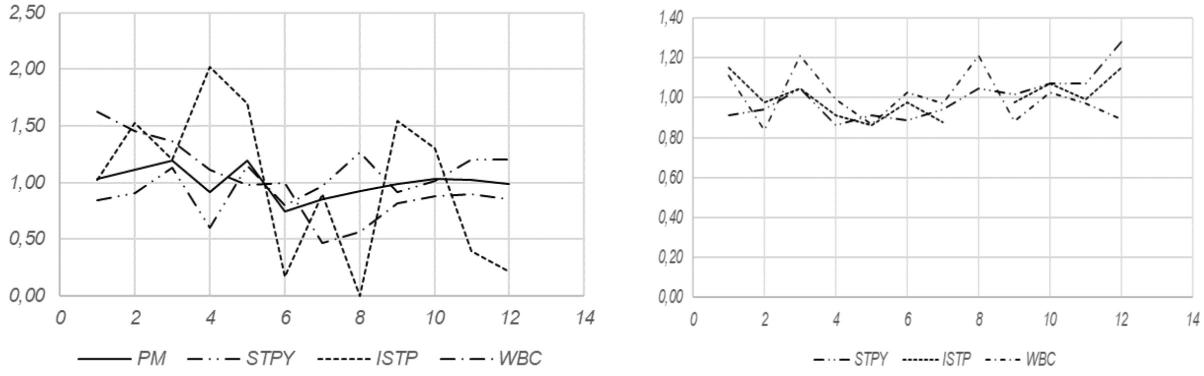
In general, the literature analysis shows that modern methods for calculating the car fleet required for transportation were formed at the end of the 19th – beginning of the 20th centuries and have not changed significantly since that time. The main tasks that are currently being considered are the structure optimization of the car fleet in the context of changing traffic volumes and the duration of car turnover, as well as increasing the efficiency of using freight cars in order to optimize the size of their fleet. The main methods of scientific research that were used by the authors of scientific works in this case are the methods of mathematical statistics, economic and mathematical modeling, as well as operations research. The relevance of this study is due to the fact that the tasks the consignors face when forming a car fleet for the transportation of their products differ from the tasks of carriers and car operators when forming car fleets to provide services to third-party consumers. And the conditions for the transportation of iron ore raw materials differ from those of transportation of other goods considered in scientific papers. Therefore, the methods for calculating the size of the car fleet needed for carrying out the transportation of iron ore raw materials requires improvement. The aim of the work is to improve the methods for calculating the size of the private car fleet to perform transportations in the context of changing the volumes of work. In the course of the study, the following tasks are being solved: study of the actual conditions of transportation of iron ore raw materials; construction of economic and mathematical model to assess the required size and structure of the car fleet to transport iron ore raw materials; selection of the method and solution of the optimization problem of the required size and structure of the car fleet to transport iron ore raw materials.

3. Solution Methodology

Mining and processing enterprises make shipments of iron ore raw materials to the address of metallurgical enterprises and seaports. These transportations are characterized by significant volumes and a relatively small number of possible destinations. Ferrexpo Poltava Mining is considered as an example. It is the largest producer and exporter of iron ore pellets in Ukraine. The modern production facilities of the enterprise ensure the production of 12 million tons of pellets per year. At the same time, the actual production volumes are 10-12 million tons. Pellets are shipped in three main directions: the Seaport of Pivdennyi (Khimichna and Berehova stations), the Port of Izmail (Izmail station) and western land border crossings (Chop, Batievo and Uzhhorod stations). These directions differ significantly in the distance of transportations, which for the Seaport of Pivdennyi (hereinafter STPY) is 514-525 km, for the Port of Izmail (hereinafter ISTP) – 831 km and for western border crossings (hereinafter WBC) – 1203-1226 km, which causes a significant difference in car turnover duration on these routes. Fig. 1, a shows the dynamics of the value of the seasonality coefficient of the loading volumes, which for the i-th ($i = 0…3$) direction ($i = 0$ corresponds to the total volume of loading PM) in the j-th month ($j = 1…12$) was determined by the formula:

$$\gamma_{ij} = \frac{\bar{Q}_{m,ij}}{\bar{Q}_{y,i}} ,$$

where $\bar{Q}_{m,ij}$ − average daily traffic volumes in the i-th direction in the j-th month; $\bar{Q}_{y,i}$ − average daily traffic volumes in the i-th direction during the year.



a b

Fig. 1 Dynamics of the seasonality coefficients value: *a* - loading volumes; *b* - car turnover

Analysis of statistical data shows that the shipment of finished products by the enterprise occurs quite evenly and the total monthly volumes of shipment vary within 0.75÷1.2 of the average annual. At the same time, the shipment volumes in certain directions change significantly. The greatest fluctuations are observed when transporting to the Izmail port, where in some months there are no shipments, and in some months, they exceed the average annual two times. Fig. 1, b shows the dynamics of the seasonality coefficient value of the car turnover, which for the i-th (i = 1…3) direction in the j-th month (j = 1…12) was determined by the formula:

$$\varphi_{ij} = \frac{\bar{\theta}_{m,ij}}{\bar{\theta}_{y,i}},$$

where $\bar{\theta}_{m,ij}$ - average car turnover in the i-th direction in the j-th month; $\bar{\theta}_{y,i}$ - average car turnover on the i-th direction during the year.

The size of the car fleet required by a mining enterprise to carry out transportation during the j-th month can be set as:

$$N_j = \sum_{i=1}^{k} \frac{\bar{Q}_{m,ij}\left(\bar{\tau}_{ij} + t_{ps}\right)}{p_{st}},$$

where $\bar{\tau}_{ij}$ − the duration of the car location outside the siding of a mining enterprise when carrying out transportation to the i-th direction in the j-th month, days; t_{ps} − standard duration of a car location on the siding of a mining enterprise, days; k- the number of directions to which iron ore raw materials are shipped.

The need to divide the duration of car turnover $\bar{\theta}_{m,ij}$ into components $\bar{\tau}_{ij}$ and t_{ps} is due to the fact that, as a rule, industrial enterprises use a simplified system for accounting the turnover duration of their cars and the duration of car location on the siding includes both the time spent on loading cars itself, idle time for repairs, and time on staging tracks, etc. It is also assumed in the calculations that the capacity reserves of the railway infrastructure and the productivity of the loading and unloading mechanisms of the consignor and consignees are sufficient to smooth out the daily irregularity of the volume of freight work. Considering that the values of $\bar{Q}_{m,ij}$ and $\bar{\tau}_{ij}$ are random, the number of cars N_j required to ensure transportations during a separate month is also a random variable. The histogram of the random variable N_j is shown in Fig. 2.

Based on the analysis of the statistical series of a random variable N_j, it was hypothesized that the parent universe has a normal distribution. Testing this hypothesis using the Pearson's goodness-of-fit test χ^2 showed that there is no reason to reject the hypothesis about the normal distribution law of a random variable of the car number, which is used by Poltava Mining and Processing Plant during a separate month for the transportation of pellets.

The technology of work with private cars and cars of the third-party operators on the loading siding is different. Private cars are supplied for loading without preliminary preparation. In the case of a drop in traffic volumes so that $N_j < n_o$ (n_o here is the number of cars of private fleet of the enterprise used for transportation), private cars go to the staging. At the same time, if $n_o - N_j \leq M_{hd}$ (here M_{hd} is the capacity of staging tracks on the siding), then the staging is performed on the own tracks of the enterprise, otherwise it is performed on the tracks of other owners for a fee c_{hd}. In the case of traffic volume increase so that $N_j > n_o$, the cars of other owners are additionally used for transportation.

Before the supply of these cars for loading, their preparation is carried out, additional costs for which are c_{pt}. The number of cars of other owners, supplied for loading during the day, should not exceed the throughput capacity of the point for preparing cars for transportation H_{pc}.

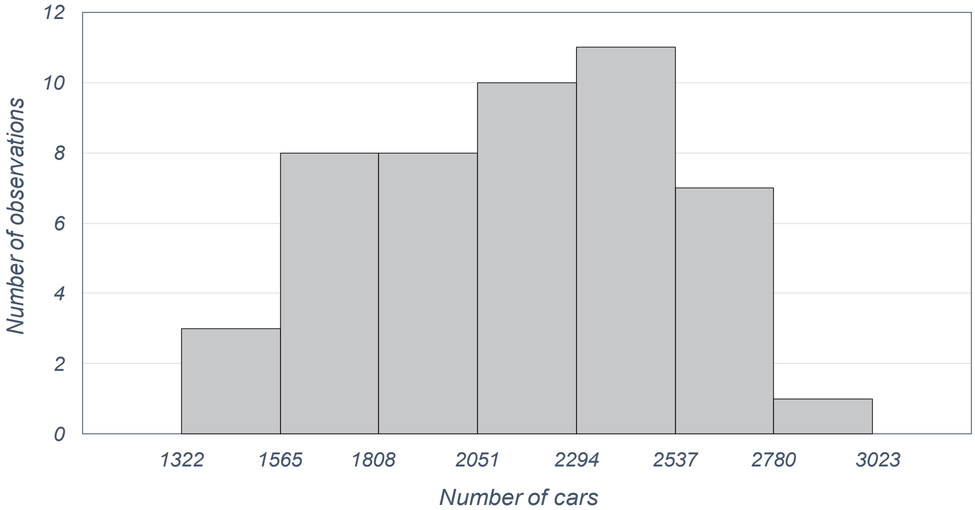


Fig. 2 A histogram of a random value of the number of cars required to carry out transportation within a month

It should be noted that a change in the car fleet might also be accompanied by a change in the capacity of staging tracks and the throughput capacity of the point for preparing cars for transportation. In this regard, we can consider k variants of the technical equipment of the siding. They are characterized by different capacities of the staging tracks $M_{hd,q}$, the throughput capacity of the point for preparing cars for transportation $H_{pc,q}$,, the cost of preparing a car for transportation $c_{pt,q}$, as well as the value of capital investments in the development of capacities for staging cars and a point preparing for transportation, respectively $C_{inf,q}$ and operation of the track infrastructure of the enterprise $C_{t,q}$ (here q is the number of variant $q = 1..k$). The terms of payment for cargo transportation services in own cars of the enterprise and the cars of the operator differ as well. When transporting iron ore in own cars of the enterprise, the transportation fee includes payment for the services of railway infrastructure and locomotive traction when transporting a loaded and empty car and is defined as:

$$c_{o,i} = c_l\left(l_i\right) + 4c_e\left(l_i\right),$$

where $c_l\left(l_i\right)$ - rate for the transportation of a loaded car on the i-th route over a distance l_i, per car; $c_e\left(l_i\right)$ - rate for the transportation of an empty car on the i-th route over a distance l_i, per axle.

When transporting iron ore in the cars of the carrier or operators, the transportation fee includes payment for railway infrastructure and locomotive traction services for the transportation of a loaded car, as well as payment for using the car:

$$c_{a,i} = c_l\left(l_i\right) + w_c\left(t_{l,i} + k_e t_{e,i}\right) + c_{ps} t_{ps},$$

where w_c − rate for using the car, UAH per day; $t_{l,i}$, $t_{e,i}$ - terms of delivery of loaded and empty cars on the i-th route; k_e – empty mileage coefficient; c_{ps} − rate for using the car during the performance of a cargo operation, UAH per hour; t_{ps} − duration of car location on the siding of a mining enterprise, hour.

Considering that the conditions for using private cars and cars of the third-party operators when transporting iron ore raw materials by a mining complex differ, the problem of optimizing the size of private car fleet arises. As a rule, such a problem arises in the case of production development and is associated with an assessment of the need to purchase an additional car fleet for mastering traffic volumes Q. The number of cars of own fleet of the enterprise is chosen as the variable x in this task. As an optimality criterion, the minimum of modified reduced PVC costs was chosen, while the objective function is formulated as:

$$PVC\left(x,Q\right) = C_{cr}\left(x - N_o\right) + C_{inf,q} + \left(\left(LCC - C_{cr}\right)x + C_{tr,q}\left(x,Q\right)\frac{1-\left(1+R\right)^{-T}}{R}\right)\left(1-\varphi\right) - xA\varphi\frac{1-\left(1+R\right)^{-T}}{R} \to \min, q = \overline{1..k}, \quad (1)$$

where C_{cr} – cost of a new car without VAT, UAH; N_o – existing private car fleet, units; LCC– life cycle cost, UAH; $C_{tr,q}\left(x,Q\right)$ − annual expenses for the transportation of the cargo volume Q with the size of the private car fleet x and the q-th variant for the siding development, UAH; R – discount rate, share; T – life cycle duration of the car, year; φ – profit tax rate, share; A – depreciation of the car per year, UAH.

The life cycle cost *LCC* of the car and its depreciation cost *A* are calculated using known methods. The annual transportation costs $C_{tr,q}(x,Q)$ for the *q*-th variant of technical equipment of the siding infrastructure of a mining enterprise are determined as:

$$C_{tr,q}(x,Q) = 365\left(\bar{N}_o(x,Q)\bar{c}_o + \bar{N}_a(x,Q)(\bar{c}_a + c_{pt,q}) + \bar{N}_e(x,Q)c_{hd}\right) + C_{t,q}\,, \tag{2}$$

where $\bar{N}_o(x,Q)$ - average daily number of the own cars of the enterprise, which is used to transport the cargo volume *Q* with a private car fleet *x*; $\bar{N}_a(x,Q)$ $\bar{N}_a(x,Q)$ − the average daily number of cars of the third-party operators, which is used to transport the cargo volume *Q* with a private car fleet *x*; $\bar{N}_e(x,Q)$ - the average daily number of private cars that are located on the staging tracks of the third-party owners when transporting the cargo volume *Q* and with the private car fleet *x*.

The values of the parameters $\bar{N}_o$, $\bar{N}_a$, $\bar{N}_e$ of function (2) can be established by the method of statistical tests (Monte Carlo method).

The values of the variable *x* in the objective function (1) are limited based on the throughput capacity of the station for preparing cars for transportation and the total amount of investment funds allocated for the development. The system of task constraints can be represented as:

$$\begin{cases} x \geq \left(1{,}15M[N] + 1{,}892\sigma[N] - \bar{\theta}H_{pc,q}\right)k_r \\ x \leq \dfrac{C_{\max} - C_{inf,q}}{C_{cr}} + N_o \end{cases}, \tag{3}$$

where $M[N]$, $\sigma[N]$ - mathematical expectation and mean square deviation of a random value of the car number required for transportation during the day, car.

The objective function (1) and the system of constraints (2) represent an economic and mathematical model that is used to assess the required size and structure of the car fleet. For a given traffic volume *Q*, for each of the *k* variants of the technical equipment of the siding, its own values of capital investments in the infrastructure development $C_{inf,q}$, and annual transportation costs $C_{tr,q}(x,Q)$ can be set within the limits (3). Based on these data, a dependence $PVC_q(x,Q)$ corresponding to this variant can be obtained. An example of the dependence of the modified reduced costs on the number of the enterprise's own cars is shown in Fig. 3. The optimum number of cars in example that shown on Fig. 3 is 4768.

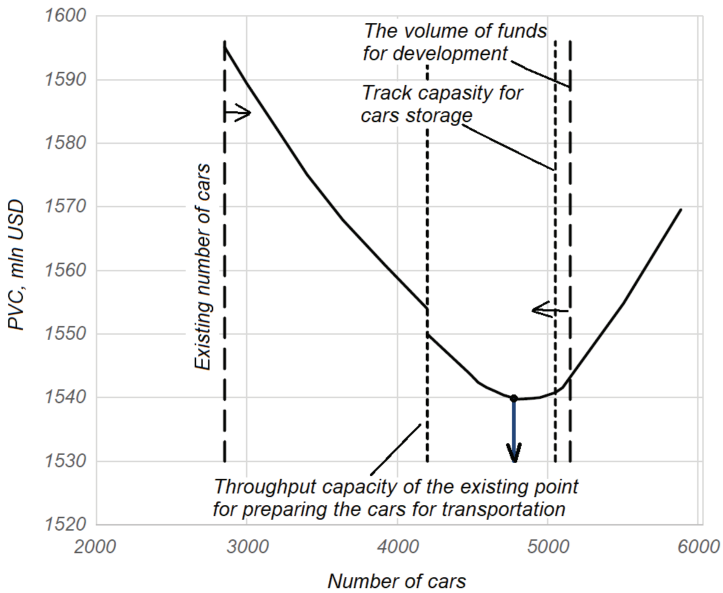


Fig. 3 The order of train formation using the nominal destination numbers PVC, mln USD

4. Research Results

Each of the dependences $PVC_q(x,Q)$, as well as function (1) as a whole $PVC(x,Q) = \min_q\left(PVC_q(x,Q)\right), q = \overline{1..k}$, are piecewise nonlinear integer functions of one variable *x*. Thus, the studies performed allow us to reduce the calculation of the size of the mining enterprise's car fleet for transportation to solving the problem of optimizing a nonlinear nonsmooth objective function of one variable under constraints. In this case, the reduced modified costs act as an objective function, and the size of the private car fleet serves as a variable. Taking into account the nature of the objective function, the problem can be solved by direct search methods, for example, the golden section method.

The work originality is due to the fact that it has improved the method for calculating the car fleet of enterprises by taking into account the differences in the loading technology of their own cars and the involved cars of operator companies. The practical value of the work lies in the fact that the proposed method allows one to reduce the logistics costs of mining enterprises due to a more accurate assessment of the costs associated with the development and operation of the car fleet, as well as the accompanying railway infrastructure of the sidings.

5. Conclusions

The studies performed allow us to draw the following conclusions:

1. The conditions for solving the problem of optimizing the size of the car fleet of industrial enterprises used to transport their own products have significant differences from the solution of the problem of optimizing the size of the car fleet of carriers and operators that are used to provide transport services. For the transportation of products of the mining industry, both own cars of the mining enterprises and cars of the carrier or operators can be used. In this regard, as a result of solving the problem of determining the size of the private car fleet required for the enterprise to master the planned volume of transportation, it is necessary to establish a rational ratio of the number of private cars of the enterprise and the cars of other owners, which, under the conditions of random factors, will allow the enterprise to ensure the lowest transportation costs. At the same time, it is necessary to take into account the difference in the conditions of rate-setting for transportations and the technology of their passage on the loading siding.

2. As a result of the study, a method was developed for solving the problem of optimizing the size of the car fleet of mining enterprises for the transportation of iron ore raw material. The proposed method is based on the formalization of this problem as a stochastic optimization problem for a nonlinear nonsmooth integer objective function of one variable under constraints. In this case, the reduced modified costs act as an objective function, and the number of private cars serves as a variable. The problem is limited by the throughput capacity of the enterprise infrastructure when servicing private cars and the cars of the other owners. The solution to the problem can be obtained by direct search methods.

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