This study investigates a transportation-technological system that enables raw material supply by rail to meet the needs of a metallurgical enterprise. The task addressed is to assess the effectiveness of centralized use of train shipments in an extensive supply network for the needs of metallurgical production. The hypothesis of the study assumes that under conditions of centralized management of the rolling stock fleet of railroad transport within an extensive supply network, its number will be smaller than in the case of a non-centralized one. A mathematical and simulation model has been built in the AnyLogic University Researcher environment using agent and discrete-event approaches. The main criterion is the minimization of the average delivery time; additional criteria are the optimal use of the working fleet of railroad cars and train locomotives. Applying them in combination makes it possible to optimize the working fleet of railroad cars and locomotives, taking into account the extensiveness of the supply network and the conditions of centralized management.

It was experimentally established that with centralized fleet management, fluctuations and volumes of metallurgical raw material residues at the enterprise depend on the loading rate of railroad cars of the sending or group of railroad cars of the stepped routes. According to the calculated values of the determination coefficients, the approximation by the exponential function turned out to be denser. The variability of raw material residues decreases with a change in the technical loading rate of the train or railroad car batch. It was established that the difference between the standard deviation for the train loading rate of 4000 t ($\sigma(x) = 4524.7$ t) and the standard deviation of 2606.5 t ($\sigma(x) = 4524.7$ t) is 1918.2 t. This corresponds to 42% of the initial value of the indicator.

The proposed approach allows for a more accurate assessment of the need for a working fleet of railroad cars and locomotives, as well as improves the efficiency of transportation management

Keywords: inventory logistics, inventory fluctuations, raw material supply, supply reliability, optimal work fleet, agent simulation

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ASSESSING THE EFFICIENCY OF CENTRALIZED USE OF TRAIN FORMATIONS WITHIN AN EXTENSIVE SUPPLY NETWORK FOR METALLURGICAL PRODUCTION

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1. Introduction

Traditionally, the size of the working fleet of cars and locomotives in the organization of railroad transportation is determined on the basis of the time required to carry out one transportation within the framework of the full technological cycle of cargo handling. This approach is based on the assumption that one unit of rolling stock, using one unit of throughput capacity, enables transportation of the corresponding batch of cargo over a certain technological time [1].

However, this calculation method is appropriate only for assessing the need for allocated throughput capacity and working fleet of rolling stock along individual directions – for example, on a stretch or section. However, its application is significantly complicated under the conditions of an extensive supply network, which includes a set of departure and destination points, especially under the condition of centralized management of a single fleet of cars and locomotives.

In such a situation, the need for a working fleet is determined separately for each direction, and then summed up with rounding up, which causes significant errors in the final estimate of the required rolling stock fleet. Such decisions necessitate an unjustified increase in the volume of investments required to purchase the required amount of rolling stock and worsen the efficiency of its use.

In view of this, the construction of models to increase the efficiency of the organization of raw material supply by accurately assessing the need for a working fleet of railroad cars and locomotives is an important and relevant scientific and applied task. The implementation of such models and assessment methods could make it possible to optimize the number of rolling stock involved in transportation, reducing the cost of transportation, and as a result, the cost of production at metallurgical enterprises.

2. Literature review and problem statement

In [2], the optimal level of basic stocks for industrial symbiosis in the production network was studied. Analysis was carried out on the basis of the constructed economic and mathematical model. At the same time, despite the fact that the study was conducted on the example of a production network, the logistics factor was not taken into account, which does not allow for optimization based on modern logistics technologies.

In another work, a specialized approach to operational management of stocks at a port warehouse was proposed [3]. The sustainability and stability of cargo operations during the arrival of ships in the port were chosen as efficiency criteria. At the same time, the system under consideration is to some extent isolated from external input and output flows. This approach is rational for optimizing internal processes, but solving complex problems requires formalizing the influence of external factors on internal operational activities.

In [4], the issue of formation and management of stocks, as well as the influence of the human factor on this process – the subjectivity of estimates of the required volumes of stocks in warehouses, was studied. It has been proven that in emergencies this leads to incorrect planning and distribution of stocks between warehouses at a certain landfill. The studies have shown that the issue of stock formation under such conditions has been considered by many researchers but is still a subject of discussion. However, the work does not provide recommendations for eliminating erroneous decisions regarding the creation of stocks and the economic assessment of the cost of excess stocks or shortages. The development of the idea of forming the stability of the system and the volume of stocks necessary for its provision is also considered in [5]. To increase the stability of the system, probabilistic demand models and failure risks are taken into account, which ensures the reliability of the supply chain. However, the optimization algorithm used, Grasshopper (GOA), requires preliminary determination and adjustment of a large number of parameters, which complicates the process of finding a solution. In [6], the problem of unauthorized access to critical public infrastructure facilities and the conditions for effective counteraction to such threats were investigated. However, the work did not investigate potential losses from system disruption and the impact on the operation of the transportation system. The security system from the standpoint of design and operational management is considered in sufficient detail in [7]. At the same time, the work does not provide experimental data or results of integer modeling to assess its effectiveness, which does not make it possible to determine the further impact of improving the security system on the regularity and stability of raw material supplies.

The general assessment of the probability of transport risks in mass transit systems was thoroughly investigated in [8], in which computer simulation was used as an experimental model. The results of numerical experiments are reported, demonstrating the relationship between the channeling of the system, its productivity and the intensity of the incoming flow. However, the work does not provide an algorithm for choosing a rational number of channels and does not reflect data on the impact of the number of channels on the stability of the system.

Study [9] considered the reliability of supply between enterprises in the USA and Mexico. The results showed that among the entire set of logistical risks, the most unpredictable are the risks associated with border crossing. It is this factor that causes significant fluctuations in delivery times and causes the formation of excess inventories. However, the work does not contain recommendations for reducing the level of excess inventories.

Another work [10] reports the results of research into high-tech hybrid production and its significant dependence on the reliability of suppliers. It is noted that under such conditions it is advisable to maintain an excess stock, which can exceed the usual volume by 20 times. At the same time, the study does not present the results of technical and economic calculations or integer modeling. Similar results were obtained in [11], but the location of the centers of consolidation of stocks and failures in the work, which are leveled at the expense of stocks, were identified as the main influencing factors. However, the work does not contain calculations regarding the economic efficiency of the proposed solutions.

In [12], experiments were conducted with a supply chain network in which vehicles are used in a closed cycle. At the same time, the work does not provide models that would make it possible to assess the effectiveness of this technology, focusing mainly on issues of operational process management.

Study [13] emphasizes the key role of rail transport for the effective functioning of metallurgical and mining complexes. At the same time, specific ways of improving the interaction between industrial and main railroad transport in different industries are not proposed. In contrast, in another work [14], using technical and economic calculations, the optimal distances and methods of delivering raw materials by rail for the needs of metallurgical enterprises are substantiated. The study was carried out on the basis of the constructed simulation model. However, the work does not study the dependence between the methods of delivering raw materials and the level of inventories in production. Most modern studies in the field of the efficiency of transport technologies, supply chains and the functioning of large industrial systems agree that computer simulation is an effective tool for solving the tasks set [15]. At the same time, there are situations when the use of analytical methods allows one to obtain more accurate results and identify patterns. For example, in [16] it is stated that together with simulation modeling tools it is advisable to use analytical methods of research. This is proven by the example of studying the railroad as a mass transit system with a queue and relative priority. The proposed methodology could be used to manage the reliability of transport systems under resource constraints. However, the paper considers a limited test site, therefore, the proposed model cannot be used to study an extensive transport network. In [17], failure patterns in a multi-component and multi-stage mass transit system, which is considered as a repair enterprise, are studied. Although agent modeling is used as a tool, the scale of the task did not require the construction of a model sufficient for studying a larger test site.

Analysis of research in the field of organizing the transportation of raw materials by railroads and increasing the efficiency of the use of railroad infrastructure reveals that existing methods do not provide the ability to assess the efficiency of centralized use of rolling stock within the network. Therefore, there is a need to devise a method that would make it possible to assess the efficiency of the use of railroad rolling stock under centralized management on an extensive network.

3. The aim and objectives of the study

The purpose of our study is to assess the effectiveness of the centralized use of train formations in an extensive supply network for the needs of metallurgical production. This will make it possible to devise a methodology for normalizing the working fleet of railroad rolling stock in centralized use on an extensive supply network.

To achieve the goal, the following tasks were set and subsequently solved:

– to build mathematical and simulation models that would make it possible to optimize the working fleet of railroad cars and locomotives, taking into account the extensiveness of the supply network and the conditions of centralized management;

– to investigate the patterns of fluctuations in raw material stocks in metallurgical production and optimize the use of the existing working fleet of rolling stock (according to the criterion of efficiency of use) depending on the technical load standard of the train, the estimated working fleet, and the intensity of incoming freight flows.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is the transportation-technological system of raw material supply by rail to meet the needs of a metallurgical enterprise.

The hypothesis of the study assumes that under the conditions of centralized management of the rolling stock fleet of railroad transport on an extensive supply network, the required size of the working fleet will be smaller than in the case of decentralized use.

During the construction of the mathematical model and the conduct of the study, the following assumptions were adopted:

– the technological process of organizing train flows at the railroad polygon is rational and complies with current instructions and regulations;

– the influence of the human factor is insignificant and does not affect the final results of the efficiency of raw material supply;

– the network of suppliers (coal mines and mining and processing plants), the railroad transport network, and the metallurgical enterprise function as a single production system. The intensity of the formation of the cargo mass before departure is consistent with the capacity of the railroad network and the intensity of raw material consumption by the metallurgical enterprise, i.e., the process is rhythmic and sufficiently reliable;

– the technical condition of the rolling stock and railroad infrastructure is satisfactory and does not have a significant impact on the efficiency of the organization of freight transportation;

– after use, railroad cars can be used for subsequent transportation regardless of the type of raw material (coal or iron ore). Locomotives and locomotive crews are available in sufficient quantities and do not limit the efficiency of organizing railroad freight transportation;

Within the framework of the study, a train formation was taken as a transport unit, which in its technological content corresponds to the normative concept of "departure route", that is, an organized train freight formation organized as a separate freight train from the place of loading to the place of unloading.

This approach allows for a comprehensive assessment of the overall need for rolling stock without detailing individual components, in particular without taking into account the required working fleet of locomotives and railroad cars, the need for locomotive crews and technical capacities for servicing rolling stock.

4. 2. Construction of a mathematical (simulation) model

The considered problem forms an optimization-mathematical model of multi-criteria optimization, in which the main criterion is the minimization of the average delivery time, and the additional criteria are the optimal use of the working fleet of railroad cars and train locomotives. The main idea is that according to logistics principles, any transportation under the same conditions should provide a minimum average delivery time. At the same time, achieving this minimum is possible only under the condition of an unlimited number of resources, which is impractical. Therefore, when optimizing the transportation-technological line of raw material supply on the network, it is advisable to use a set of optimization criteria. The main (general) criterion is the minimum or average delivery time of goods, while additional minimization criteria, introduced in the form of restrictions to the objective function, are aimed at the rational use of available production resources of transport – the level of loading of rolling stock (train formations) and network capacity. Given the specificity of the task related to the management of raw material stocks in metallurgical production and the need to ensure sustainable and reliable functioning of the technological process of metallurgical production and a systematic approach in the system (raw material extraction – transport – metallurgical production), additional criteria have also been defined as minimizing fluctuations in the volume of residual stocks of iron ore concentrate and coking coal at the metallurgical enterprise.

Since the task involves centralized management of the existing fleet of vehicles in an extensive supply network, taking into account the variability of the duration of technological processes and the intensity of cargo arrival, its numerical implementation is possible only using computer simulation.

The simulation model was built in the AnyLogic University Researcher environment using agent and discrete-event approaches. This made it possible to recreate in detail the technological processes of train formation turnover and their interaction with the network of departure points (coal mines and mining and processing plants) and the destination point (metallurgical enterprise). The use of the agent approach made it possible to model the complex technological process of railroad interaction with departure and destination points as a single large transport and production system.

5. Results of assessing the effectiveness of centralized use of train formations in an extensive supply network for the needs of metallurgical production

5. 1. Results of building a mathematical (simulation) optimization model of the transport process in an extensive supply network for the needs of metallurgical production

The delivery time of a consignment of goods on the railroad network is formalized as the total duration of technological operations from the moment of the start of the process of accumulating the cargo mass to the loading rate into the train formation until the moment of completion of unloading the cargo at the destination

$$t_{deliv.} = t_{accum.} + t_{w.arriv.} + t_{w.load.} + t_{load.} + t_{depart.oper.} + t_{move.to.dest.} + t_{w.unload.} + t_{unload.}, \qquad (1)$$

where $t_{accum.}$ – duration of time for accumulation of cargo to the loading rate in the train formation; $t_{w.arriv.}$ – duration of waiting time for railroad cars to be loaded; $t_{w.load}$ – duration of waiting for loading; t_{load} – duration of loading; $t_{depart.oper}$ – duration of operations for sending the train formation; $t_{move.to.dest.}$ – duration of movement of the train formation to the destination station; $t_{w.unload.}$ – duration of waiting for unloading; $t_{unload.}$ – duration of unloading.

Considering that the values of the components of expression (1) will significantly depend on the technological features of each of the route options and departure points, the key in estimating the cargo delivery time will be the average value, which can be formally represented as a dependence on the set of technical and technological parameters of the raw material supply network

$$\overline{t_{deliv.}} = \frac{\sum_{i=1}^{N_v} f\left(\{T_1 : T_{N_v}\};\{Th_1 : Th_{N_v}\};\{S_1 : S_{N_v}\}\right)_i}{N_v}, \tag{2}$$

where N_v is the total number of train formation options; $f\left(\{T_1 : T_{N_v}\};\{Th_1 : Th_{N_v}\};\{S_1 : S_{N_v}\}\right)_i$ is a function that determines the time of cargo delivery on the i-th route; $\{T_1 : T_{N_v}\}$ is a set of technical parameters of the i-th supply route; $\{Th_1 : Th_{N_v}\}$ is a set of technological parameters of the i-th supply route; $\{S_1 : S_{N_v}\}$ is a set of organizational parameters of the i-th supply route.

Technical parameters should be understood as the throughput and processing capacity of the separation points of railroad stations and inter-station sections, as well as train mass standards and other conditions of technical operation on a specific railroad route.

Technological parameters should be understood as the time standards required to perform technological operations, as well as the features of technological processes related to the functioning of railroad stations and sections adjacent to them.

Organizational parameters should be understood as the method of organizing traffic, as well as interaction with the approach tracks of the departure and destination stations.

Another criterion for the optimal organization of raw material supply by train formations may be minimizing fluctuations in raw material stocks and ensuring the most stable rhythm of supply. This can be expressed through the variation of supply volumes in the reporting period

$$Q_{var} = f\left(\frac{\sigma_{r.p.}}{M(x)_{r.p.}}\right), \tag{3}$$

$\sigma_{r.p.}$ – standard deviation of raw material stocks of the j-th group during the reporting period; $M(x)_{r.p}$ – estimated mathematical expectation of raw material stocks of the j-th group during the reporting period.

Transport support of metallurgical production involves the supply of two main groups of raw materials – iron ore concentrate (or iron ore) and coking coal. Since these groups have different degrees of fluctuations during the reporting periods and also taking into account the results of experimental assessment, the coefficient of variation for these two groups should be considered separately.

So, this is a multi-criteria optimization problem, where the main criterion is the average delivery time of goods. Additional criteria are:

– minimization of fluctuations in stock volumes during the reporting period, expressed through coefficients of variation separately for iron ore concentrate and coking coal;

– optimal use of the fleet of railroad cars and locomotives in accordance with the recommendations [18];

– minimal load on the capacity of railroad lines.

Then the final optimization mathematical model will take the following form:

$$\overline{t_{deliv.}} = \frac{\sum_{i=1}^{N_v} f\left(\{T_1 : T_{N_v}\};\{Th_1 : Th_{N_v}\};\{S_1 : S_{N_v}\}\right)_i}{N_v} \to \min, \tag{4}$$

$$\begin{cases} Q_{var_{iron.ore}} \to \min, \\ Q_{var_{cok.coal}} \to \min, \\ N_{dedic.band.} \to \min, \\ \psi(N_{warh.}) \geq 0.5, \\ \psi(N_{warh.}) \leq 0.75, \end{cases} \tag{5}$$

where $Q_{var_{iron.ore}}$ – coefficient of variation of iron ore reserves during the reporting period; $Q_{var_{cok.coal}}$ – coefficient of variation of coking coal reserves during the reporting period; $N_{dedic.band.}$ – daily allocated capacity for organizing scheduled transportation. This parameter can be expressed in the total volume of train movements with iron ore concentrate and coking coal throughout the supply network; $\psi(N_{warh.})$ – coefficient of utilization of the vehicle fleet.

The constructed simulation model includes the following key agents:

1. Agent 1 – a central agent that ensures coordination and interaction of all other agents within a single computer simulation system.
2. Agent 2 – an agent that reproduces the technological process of train turnover between the network of raw material suppliers (coal mines and enrichment plants) and the recipient (metallurgical enterprise).
3. Agent 3 is a population of agents that simulates the origin of freight flows and the formation of demand for transportation. It reflects the network of raw material senders (coal mines and enrichment plants).
4. Agent 4 is a population of agents that simulates train formations. They are responsible for compliance with technical loading standards and form the available working fleet of railroad trains.
5. Agent 5 is a population of agents of the "order" type, which reflect the emergence of a need to transport cargo batches between specific points of departure and destination.
6. Agent 6 is an agent "metallurgical production", which simulates the intensity of consumption of various types of raw materials (in particular, coking coal and iron ore).

For the numerical implementation of the optimization model (4), the initial data of the basic experiment reported in [19] were used. To conduct a series of experiments on the sensitivity of the model, the ranges of variable parameters given in Table 1 were used.

Table 1

Input data for the optimization experiment

No. of order	Parameter ID	Units of measurement	Range of values, amount of change	Note
1	Estimated number of train formations – sending trains	units	5–100; 1	Centralized train formation management
2	Train load capacity, $q_{railw.route}$	tons	1,000–4,000; 1,000	Without centralized management

The model assumes a step-by-step change of the indicators specified in Table 1 for the most complete reflection of the dependences. The step of 1000 t is provided based on the real volumes of loading of rolling stock in the sending train.

5. 2. Results of experimental studies with a simulation model of the transport process on an extensive supply network for the needs of metallurgical production

As a result of a series of experiments using the constructed simulation model of the transport process, the following results were obtained. The average delivery time of iron ore concentrate and coking coal, under centralized management conditions, with a sufficient size of train formations, does not depend on the size of the working fleet and the technical loading rate.

The values of the average delivery time are:

– iron ore – 58.8 hours;

– coking coal – 98.4 hours;

– the overall average value – 62.5 hours (Table 2).

The density of the distribution of cargo delivery time, depending on the estimated number of train formations and their loading rate, is subject to the normal distribution law, regardless of the technical loading rate (Fig. 1).

At the same time, there is a directly proportional relationship between the technical loading rate and the standard deviation of delivery time: the lower the technical loading rate, the smaller the standard deviation of the average delivery time of iron ore (Fig. 2).

A detailed analysis of the random variables of the residual volumes of iron ore concentrate depending on the technical loading rate of railroad units is given in Table 3. From Table 3 it is clearly seen that the mathematical expectation of the residual iron ore concentrate is greater, the lower the technical loading rate of train units or railroad car lot. In other words, there is an inverse proportional relationship.

For a detailed analysis of the dependences (Table 3), plots of functional relationships of residual reserves of train formations or groups of railroad cars with cargo entering the metallurgical enterprise were constructed. The plots also display the dependences of the lower limits of the standard deviation and double standard deviation (Fig. 3, 4). According to the calculated values of the coefficients of determination, the approximation by the exponential function turned out to be denser.

Since the distribution of residual reserves is close to normal, the lower limit of the double standard deviation determines the 95% confidence interval.

The least squares method established theoretical dependences between the technical loading rate of iron ore concentrate volumes entering the metallurgical enterprise and the average level and limit fluctuations of iron ore concentrate residues at the enterprises.

Table 2

Experimental results

Indicator	Train load capacity, tons			
	1,000	2,000	3,000	4,000
Average delivery time, hours:				
Iron ore	58.8	58.8	58.8	58.8
Coking coal	98.3	98.3	98.3	98.4
Total, with centralized train formation management	62.5	62.5	62.5	62.5
Average daily train traffic	33.4	16.7	11.1	8.3
Average daily carrying capacity, tons	33,400	33,400	33,400	33,400

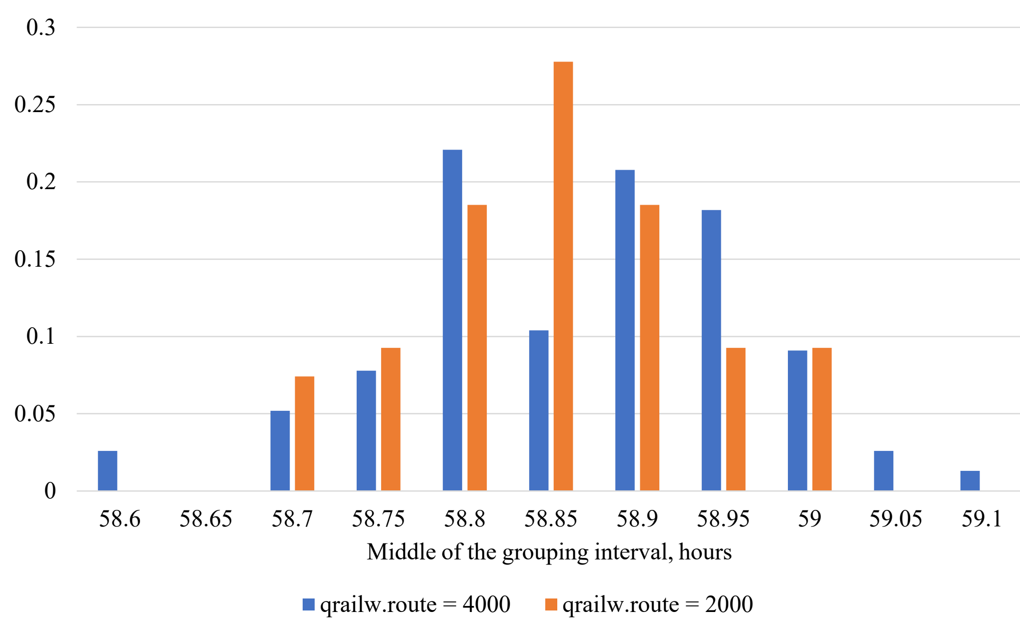

Fig. 1. Density of distribution of average iron ore delivery time with centralized management of train formations and their sufficient number ($\psi(N_{warh.}) < 0.9$), depending on the technical loading rate

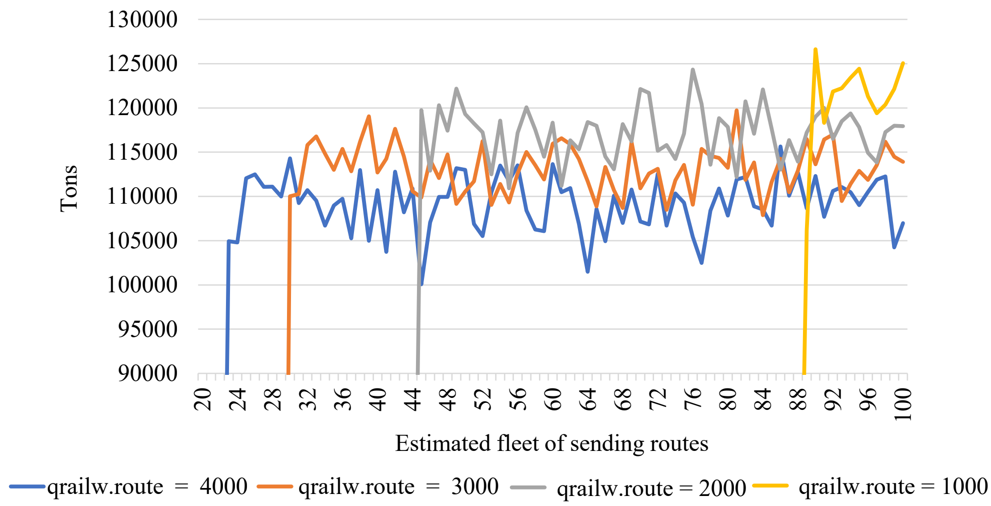

Fig. 2. Fluctuations in residual iron ore reserves depending on the estimated number of train formations and their loading rates

Table 3

Results of analyzing statistical samples of fluctuations in residual iron ore reserves at a metallurgical enterprise depending on the number of train formations

Indicator	Train load capacity $q_{railw.route}$, tons			
	4,000	3,000	2,000	1,000
Reserve for the beginning of the process, tons	200000,0			
Mathematical expectation, *M*(*x*), tons	109,179.7	113,160.6	117,192.3	121,318.8
Standard deviation, $\sigma(x)$, tons	4,524.7	3,887.5	3,351.3	2,606.5
Lower limit of stocks $M(x) - \sigma(x)$, tons	104,655.0	109,273.1	113,841.0	118,712.3
Lower limit of stocks $M(x) - 2\sigma(x)$, tons	100,130.2	105,385.5	110,489.7	116,105.8

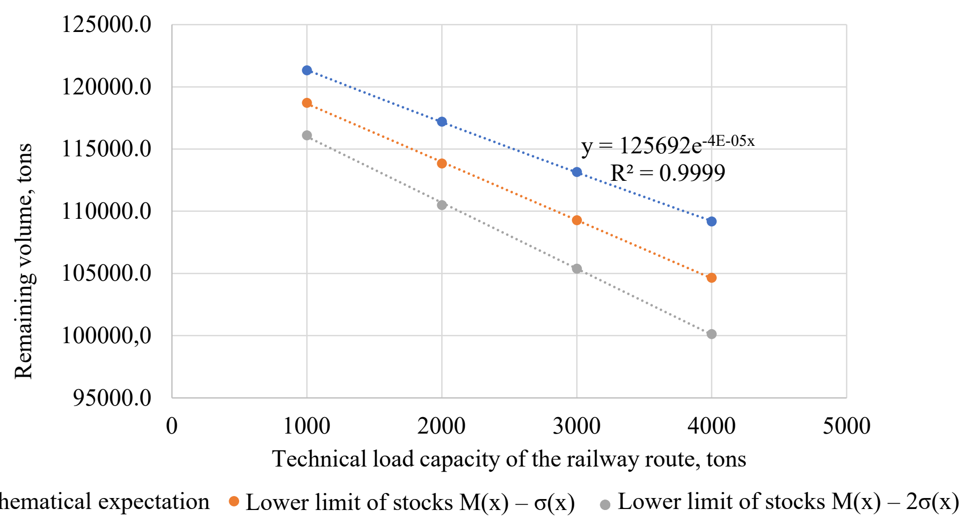

Fig. 3. Dependence of the average remaining volume of iron ore at a metallurgical enterprise on the technical loading rate and for a sufficient number of train formations ($\psi(N_{warh.}) < 0.9$)

Considering that the volume of iron ore residues, in addition to all of the above, also depends on the initial residue at the beginning of the observation (Table 3), the dependence of the standard deviation value on the technical loading rate of the train formation is more indicative (Fig. 4).

Fluctuations in coking coal reserves at a metallurgical enterprise, provided there is a sufficient number of train formations, almost do not change even with an excessive increase in the number of units of the working fleet (Fig. 5, Table 4).

To identify patterns in the formation of coking coal reserves depending on the loading rates of train formations, an analysis of experimental data series was conducted; theoretical dependences were determined using the least squares method (Fig. 6).

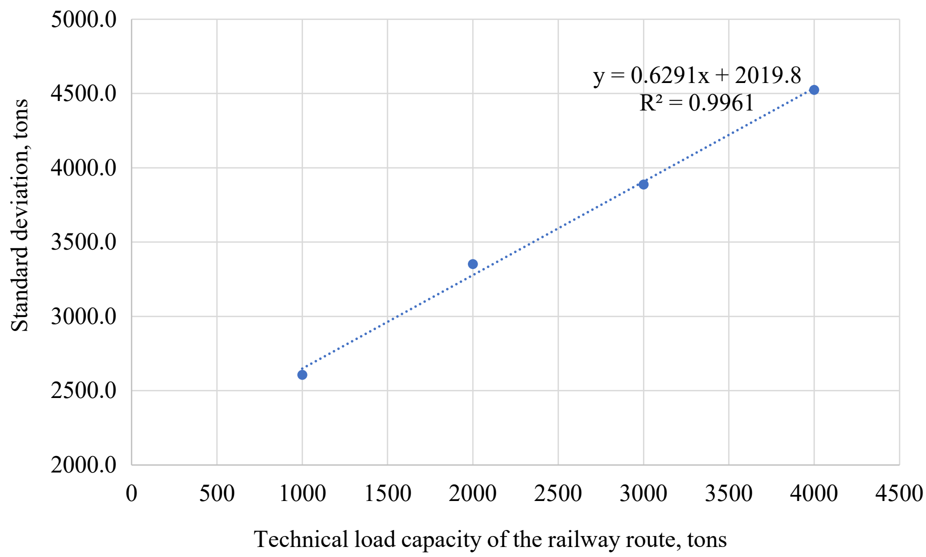

Fig. 4. Dependence of standard deviation of the volume of iron ore residue at a metallurgical enterprise on the technical loading rate and for a sufficient number of train formations ($\psi(N_{warh.}) < 0.9$)

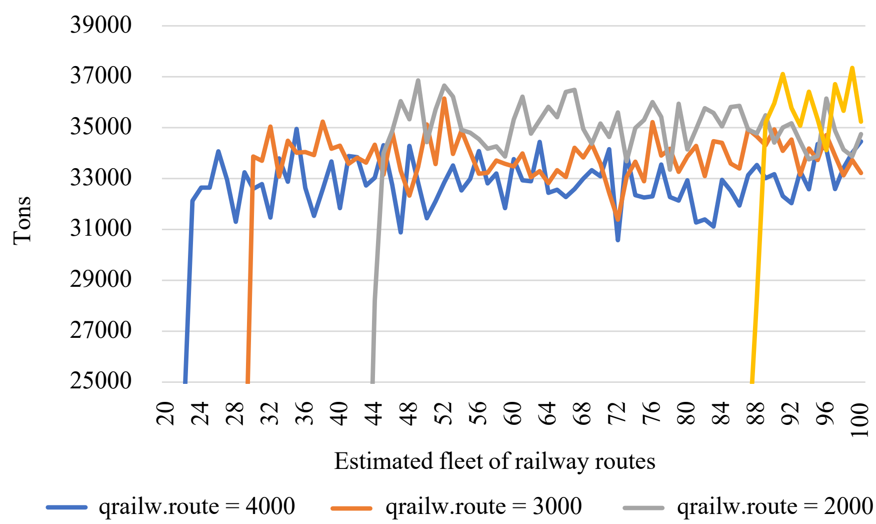

Fig. 5. Fluctuations in residual coking coal reserves depending on the number of train formations and their loading rates

Table 4

Results of analyzing statistical samples of fluctuations in residual coking coal reserves at a metallurgical enterprise depending on the number of train formations and their loading rates

Indicator	Train formation loading rate $q_{railw.route}$, tons			
	4,000	3,000	2,000	1,000
Reserve for the beginning of the process, tons	50,000.0			
Mathematical expectation	30,914.5	32,265.9	33,889.4	35,960.2
Standard deviation	1,936.7	1,563.6	1,216.3	923.9
Lower limit of stocks $M(x) - \sigma(x)$	28,977.7	30,702.3	3,2673.0	35,036.3
Lower limit of stocks $M(x) - 2\sigma(x)$	27,041.0	29,138.7	31,456.7	34,112.4

The dependence of car turnover time on the utilization rate of train formations has the same nature, regardless of the technical norm of their loading (Fig. 7).

When studying patterns in the influence of technical loading rate $q_{railw.route}$ on the rate of utilization of train formations $N_{warh.}$ it was found that for different ranges of optimal utilization of train formations $\psi(N_{warh.})$ a dense index theoretical dependence is observed (coefficient of determination $R^2 = 1$) for different values of the working fleet utilization coefficient $\psi(N_{warh.})$ (Fig. 8, Table 4).

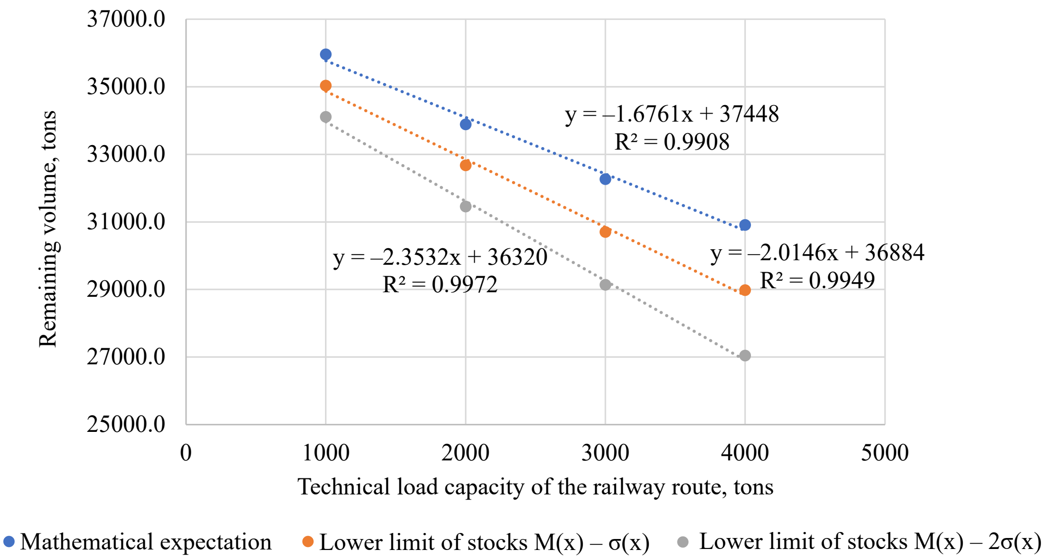

Fig. 6. Dependence of the average residual volume of coking coal at a metallurgical enterprise on the technical loading rate and for a sufficient number of train formations ($\psi(N_{warh.}) < 0.9$)

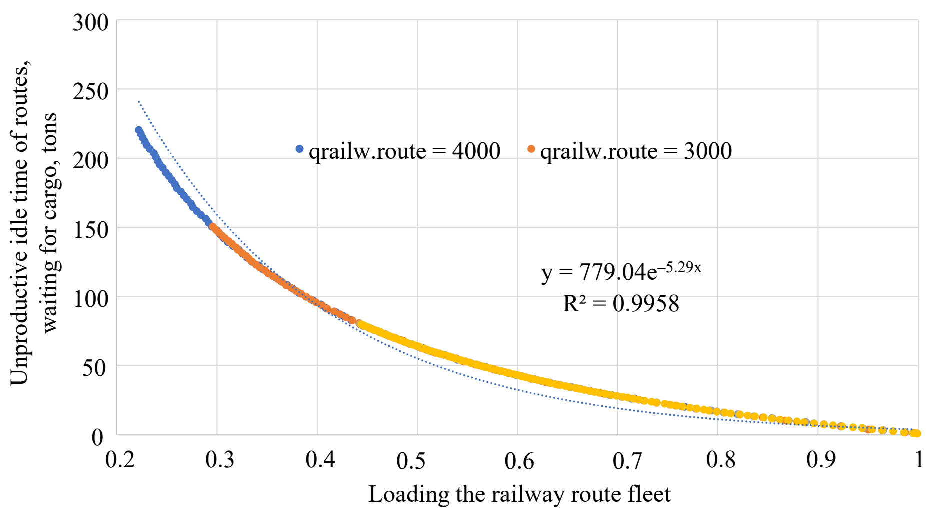

Fig. 7. Experimental and theoretical dependence of car turnover time $Q_{stock.turnov.}$ on the train formation utilization factor $\psi(N_{warh.})$

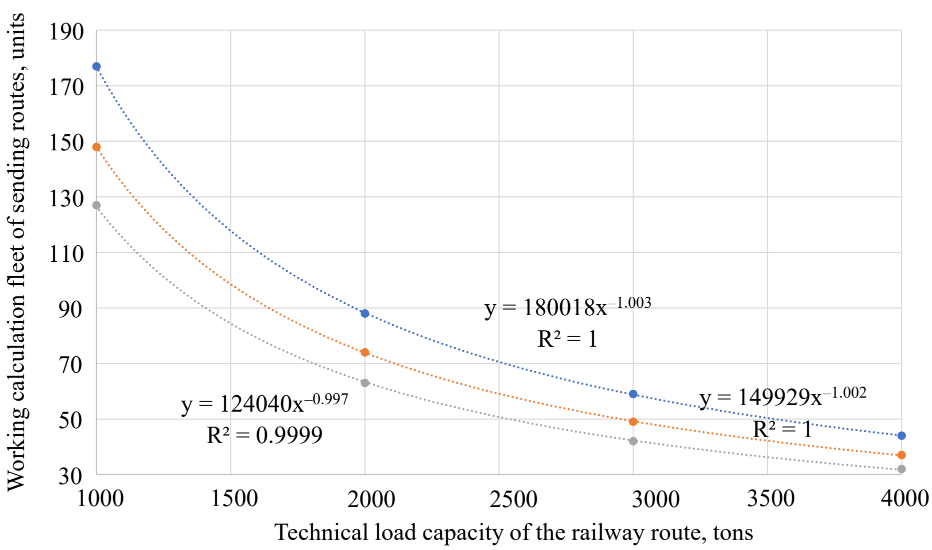

Fig. 8. Dependence of the calculated number of train formations N_{warh} on the technical loading rate $q_{railw.route}$ for different values of the train formation utilization factor $\psi(N_{warh.})$

The indicative theoretical dependence shows that an increase in the technical loading rate leads to a more rational use of rolling stock, and therefore to a decrease in the need for railroad cars and train locomotives. That is, with a linear increase in the technical loading rate, the need for rolling stock decreases exponentially. This same effect applies to the use of available capacity.

6. Results of investigating the effectiveness of centralized use of train formations within an extensive supply network: discussion

Analysis of the volumes of residual stocks of iron ore concentrate and coking coal at a metallurgical enterprise depending on the technical loading rate of the train formation reveals that, regardless of this rate, significant fluctuations in residual stocks are observed (Fig. 2, 5). At the same time, the average values of residual stocks during the observation period were the higher, the lower the technical loading rate of the train formations was (Fig. 3, 4, 6, Tables 3, 4). This phenomenon is explained by the fact that with an increase in the technical loading rate, with constant transportation volumes, cargo batches will arrive at the end consumer at longer intervals, but each of them will have a larger volume. As a result, the rhythm of supply decreases, and fluctuations in cargo flow volumes increase.

This is true provided that its size is sufficient, i.e., the fleet loading during the day is less than 90%. The result is explained by the fact that under conditions of sufficient or even excessive number of train formations, the delivery time is determined mainly by technical and technological norms of time spent on performing operations – that is, the conditions of technical operation of railroads. These conditions include, in particular, route speed, established technological norms of servicing trains and railroad cars at railroad stations while inter-operational downtime is practically absent. This conclusion is also confirmed by a number of studies on running of trains within a rigid and flexible schedule [8, 20–24].

However, the most important result of our study is that with a decrease in the technical loading rate of a train formation or a railroad car batch arriving at a metallurgical enterprise, there is a decrease in the variability of the indicator, in particular the standard deviation. Thus, the difference between the standard deviation for $q_{rail.}$ = 4,000 t ($\sigma(x)$ = 4,524.7 t) and the standard deviation for $q_{rail.}$ = 2,606.5 t ($\sigma(x)$ = 4,524.7 t) is 1,918.2 t, which corresponds to 42% of the initial value of the indicator (Fig. 3, 6).

Our results indicate that with a decrease in the intervals of arrival of cargo batches, even if their volumes decrease, the variability of raw material residues at a metallurgical enterprise significantly decreases. At the same time, the question arises of the rational use of capacity, which is a valuable resource for public railroads. Since in this experiment it was considered that the available throughput capacity is sufficient, this aspect was not taken into account, therefore it is advisable to consider it in further studies.

In addition, the study focused exclusively on ensuring the technological reliability of the supply process, without taking into account the economic component, in particular the cost of delivering a ton of raw materials. It is obvious that with the increase in the intensity of the arrival of cargo batches to the final destination (metallurgical enterprise), the cost of delivering a ton increases. This aspect also needs to be taken into account in further studies.

7. Conclusions

1. A multi-criteria mathematical optimization model has been built, which, unlike existing ones, takes into account the centralized management of train formations as technological transport for the needs of the network of mining enterprises and metallurgical production.

The main optimization criterion is the average cargo delivery time within the supply network. It takes into account such factors as:

– capacity of railroad routes;

– established speed regime (average route speed).

Additional optimization criteria are:

– minimization of iron ore concentrate and coking coal stocks;

– minimization of the load on the railroad infrastructure by reducing the used capacity;

– optimal use of train formations.

To implement the study, a previously built simulation model was refined, which is an agent simulation based on discrete-event processes. The model includes a set of agents that reproduce the technological processes of train formation circulation, the functioning of technological lines for the extraction of raw materials, their transportation and use at a metallurgical enterprise. The model also includes a developed parameter sensitivity analysis module and an optimization module. The model combines the processes "raw material extraction – transportation on an extensive railroad network – metallurgical production" into one technological system.

The model is implemented through computer simulation on the example of one of the typical metallurgical plants in Ukraine.

2. It has been experimentally established that with centralized fleet management, fluctuations and volumes of metallurgical raw material residues of the enterprise depend on the loading rate of freight train sets or groups of railroad cars. The obtained experimental data are closely approximated by exponential and linear dependences.

The degree of variability of the raw material residues (iron ore and coking coal) decreases, depending on the technical loading rate of the train formation or the railroad car batch that arrives at the metallurgical enterprise. It was experimentally established that the difference between the standard deviation for $q_{rail.}$ = 4,000 t ($\sigma(x)$ = 4,524.7 t) and the standard deviation for q_{rail} = 2,606.5 t ($\sigma(x)$ = 4,524.7 t) is 1,918.2 t, which corresponds to 42% of the initial value of the indicator.

It was experimentally established that the minimum fluctuations in the volume of raw material stocks (iron ore concentrate and coking coal) at the metallurgical enterprise are observed under the condition of the optimal loading rate of the train formation of 1000 t at the optimal level of use of the train formations within 0.5.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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