UDC 656.222.6; 658.785.1
DOI: 10.15587/1729-4061.2024.310679

SUBSTANTIATING THE RELIABILITY CONDITIONS FOR THE PRODUCTION PROCESS AT METALLURGICAL ENTERPRISES THROUGH THE FAULT-TOLERANT FUNCTIONING OF THE SYSTEM «EXTRACTION OF RAW MATERIALS – TECHNOLOGICAL RAILROAD ROUTES – METALLURGICAL PRODUCTION»

Oleksandr Zaruba
Department of Transport Service and Logistics*
Andrii Okorokov
Corresponding author
PhD, Associate Professor
Department of Transport Service and Logistics*
E-mail: andrew.okorokoff@gmail.com
Roman Vernyhora
PhD, Professor
Department of Transport Junctions*
Iryna Zhuravel
PhD, Associate Professor
Department of Transport Service and Logistics*
Nataliia Barkalova
PhD, Associate Professor
Department of Transport Service and Logistics*
*Ukrainian State University of Science and Technologies
Lazaryana str., 2, Dnipro, Ukraine, 49010

The object of this study is the process of formation of insurance reserves at enterprises in the metallurgical industry. Under conditions of uneven supply of raw materials to metallurgical enterprises due to disruption of the transportation process or other reasons, there is a need to create insurance stocks in order to ensure the continuity of production. At the same time, it is necessary to take into account existing restrictions, such as the limited capacity of railroad sections and the impossibility of organizing parallel movement of trains, etc. The presence of these limitations makes it impossible to use classical methods for solving similar problems, such as linear programming. Therefore, to resolve the task, a simulation model was built, based on the discrete-event principle in the AnyLogic University Researcher environment using Oracle libraries and the Java SE compiler. With the help of the model, the process of rotation of dispatch routes at the railroad yard with multiple suppliers and one consignee was formalized. The optimization criterion was chosen to be the minimum deviations of fluctuations in reserves of iron ore concentrate and coke. Analysis of the simulation results revealed that the optimal size of the fleet of railroad routes on the selected rotation polygon is 30 units; at the same time, their utilization rate will be 65 %. It was also established that fluctuations in raw material stocks have a «natural character», which is confirmed by the normal distribution of the density of stock volumes. Under these conditions, the value of fluctuations in the volumes of the main raw materials will be ±13115 t/day for iron ore concentrate, and ±5298 t/day for coke. Reducing the range of fluctuation of raw materials volumes could make it possible to optimize the costs of creating stocks and streamline the transport work of the enterprise for providing raw materials

Keywords: insurance stock, dispatch route, discrete-event principle, population of agents, level of fault tolerance

Received date 13.05.2024
Accepted date 02.08.2024
Published date 30.08.2024

***How to Cite:** Zaruba, O., Okorokov, A., Vernyhora, R., Zhuravel, I., Barkalova, N. (2024). Substantiating the reliability conditions for the production process at metallurgical enterprises through the fault-tolerant functioning of the system «extraction of raw materials – technological railroad routes – metallurgical production». Eastern-European Journal of Enterprise Technologies, 4 (3 (130)), 37–48. https://doi.org/10.15587/1729-4061.2024.310679*

1. Introduction

The supply to metallurgical enterprises requires significant coordination of efforts and scientifically based decisions in the planning and implementation of transport and technological models. The main volumes of supply are raw materials, mainly iron ore and iron ore concentrate, as well as energy components of production, such as coke and coking coal. It is important to note that the complex supply process is complicated by significant flow variability and an extensive network of raw material dispatch points, especially for iron ore and iron ore concentrate. Thus, there is a scientific and applied problem related to the extensive network of shipment and destination of goods.

On the one hand, this problem belongs to classic transport problems and can be solved by optimizing total operating costs or a technological criterion. However, traditional methods of analytical modeling, such as the simplex method or linear (and even stochastic) programming, are not able to take into account the ramifications of the network and all the stochastic processes that occur during the organization of the supply of metallurgical enterprises. In addition, these methods do not provide the possibility of taking into account the optimal use of resources and ensuring an acceptable level of reliability of transport and technological systems, in particular, with regard to the rational use of the transport fleet. Thus, the research of the specified issues is a relevant task.

2. Literature review and problem statement

Increasing the efficiency of railroad freight and passenger transportation over the last decade remains one of the key problems of improving technological processes and the process of managing the infrastructure of railroad transport systems [1] in many countries of the world. The dependence of the metallurgical and other resource industries on the effective functioning of railroad transport in countries with a corresponding economy remains critical. For South Africa, it is critical for metallurgical and other raw material industries [2]. For the Canadian economy, railroad transport plays a significant role in the processing, raw materials, and oil industries [3].

Ukrainian railroads remain key in providing the metallurgical, mining, processing, and agricultural industries. This is proved by the institutional analysis given in [4].

Indian Railroads is one of the most extensive networks in the world. According to study [5], the government has developed a conceptual program to reduce greenhouse gas emissions precisely at the expense of railroad transport, which is able to simultaneously meet the transportation needs of the country's economy and have a minimal impact on the environment. Similar problems are analyzed in [6] for the countries of southern Europe and France [7].

The rapid development and problems of network planning and performance evaluation are also observed in the West African region. Paper [8] reports the results of SWOT/AHP analysis of the state of structural hierarchies of the railroad network. Broader strategies for the integration of railroads into local and regional infrastructure have been developed. At the same time, the work does not specify the details of integration strategies; only the possible consequences are given.

In [9], the concept of an intelligent decision-making system for the organization of ore transportation is proposed. The main feature of this system is taking into account forecasts of raw material production volumes, and therefore the possibility of transportation planning, which is very close to the problems of this work. A similar scenario is explored in work [10], in which the authors justify the appropriate use of neural networks in planning the technological process and ensuring the reliability of railroad transportation. At the same time, in the cited works [9, 10], the results of statistical modeling for a certain historical period are taken as a basis and the current situation on the network is almost not taken into account.

Analysis of the latest research in the area of optimization of railroad transport systems makes it possible to state that computer simulation tools are becoming increasingly popular for the optimization of transport processes and cargo delivery. Thus, in [11], the authors simulate a complex multimodal supply chain of bulk cargo. The average delivery time was chosen as the optimization criterion, which quite strongly narrows the possibilities of multi-criteria computer simulation. In study [12], on the basis of computer modeling, the technical and technological parameters of main and industrial railroad stations are investigated and optimized; at the same time, the modeling is based only on discrete-event approaches, which cannot be considered modern. In study [13], with the help of computer stochastic modeling, the profit from the management of the car fleet in the loaded and empty state is optimized. The presented model made it possible to optimize the structure of the fleet of vehicles with significant fluctuations in cargo flows. At the same time, the research does not take into account the carrying capacity and technical norms of operation of railroad routes.

In other studies, for example [14], the railroad network was optimized using the developed simulation modeling platform RailNet. At the same time, most of the technological parameters, in particular cargo flows and their fluctuations, are not taken into account in the cited studies.

Despite the wide range of tools and opportunities provided by modern information and simulation systems, many authors use analytical tools in their research. For example, in work [15], with the help of a genetic algorithm, the capacity is distributed between freight and passenger train traffic. In [16], the methodology for determining the optimal location of iron ore concentration transit logistics nodes is given. Similar to these works is that the authors rely on the determinism of flows and processes, which calls into question certain conclusions in their studies.

Paper [17] provides a model for optimizing supply routes, which is also based on the determinism of processes and the discreteness of parameters. This approach is somewhat outdated and significantly inferior in reliability to stochastic modeling.

Study [18] reports the results of experiments in the form of dependences of costs on the order of organization of transportation in freight complexes of railroads. If production inventories are considered as certain costs, this toolkit is similar to the one used in this study. However, the authors did not take into account most of the technological parameters of the system, mainly the processing capacity of transport systems.

Unlike previous studies, in works [19, 20] the authors took into account the carrying capacity of railroad lines when optimizing supply routes. However, the presented models are valid only for extreme periods associated with the repair of railroad tracks. A similar problem was also solved in study [21] for the realities of Ukrainian railroads with a branched and busy network. And although the authors presented the dependences of the formation of reliable functioning conditions, the transport processes are considered as classic systems of mass service, which is not inherent in railroad transport systems.

In [22], the reliability of freight train traffic schedules was investigated based on the methods of mathematical statistics. Studies show that it is most expedient to organize the movement of freight trains according to the schedule for technological routes that meet the needs of industries with deterministic consumption of raw materials, for example, metallurgical, energy, oil refining, etc. [23]. In addition, this transportation technology also contributes to increasing the safety of the transportation process [24]. The authors of these works have carefully researched the technological and safety aspects of the transportation process but the issue of the influence of transportation technologies on the work of cargo-receiving enterprises is not considered, although such an influence definitely exists. The specified result is explained by the limitation of the chosen scientific mathematical methods – linear programming, and the deterministic approach to the selection of initial parameters.

In other studies, the schedule of train traffic [25] and the scheduled maintenance schedule of railroad transport infrastructure are optimized by linear programming methods [26]. In these studies, based on a series of experiments with appropriate computer models, the most fault-tolerant infrastructure operation and maintenance plans were determined. And although the authors study reliability as a system indicator, the research does not take into account the formation plan and schedule of trains.

The problem of effective distribution of the carrying capacity of railroad lines among many participants of the transport market is considered in [27]. The authors propose an allocation algorithm that determines the shortest time for bandwidth allocation between bidders. The question of consistency of train schedules on adjacent sections remains beyond the scope of the study. In [28], the authors draw the attention of the scientific community to the problem of limited capacity of railroad transport systems and the critically important problem of its rational distribution. However, effective tools for solving these problems are not given in the research.

In [29–33], methods of resource conflict graphs are used, with the help of which, on the example of Swiss railroads, the problem of replanning in the distribution of capacity is optimized. At the same time, only the production capacities of railroads were chosen as resources, and the interests of customers and other participants of the transport market were almost not taken into account.

Thus, our review of earlier studies revealed significant developments in terms of assessing and ensuring the reliability of the transportation process in medium trunk and industrial railroad lines and an almost complete absence of studies on the complete production system of the type «raw material extraction – supply – consumption of raw materials». The scientific community's lack of attention to this issue is explained by the limitations of analytical methods for such large-scale and complex tasks: the impossibility of modeling stochastic processes in multifactor and multicriteria tasks. This problem can be solved using more modern and powerful methods, such as simulation modeling.

3. The aim and objectives of the study

The purpose of our study is to determine the limits of stability for the system of creating insurance reserves of raw materials, which enables trouble-free functioning of the technological processes in metallurgical production. This will make it possible to optimize the process of supply, creation, and maintenance of insurance stocks of raw materials and determine the limits of sustainability in the stock system.

To implement the goal, the following tasks were set:

– to build a simulation model of transportation of iron ore concentrate and coal (coke) by railroad technological routes between their production (mining and processing plants, coke chemical enterprises) and consumption (metallurgical enterprise);

– to establish regularities in the formation of insurance reserves of raw materials for the needs of metallurgical production.

4. The study materials and methods

The object of our study is the process of supplying raw materials for the needs of metallurgical production by rail transport.

The main hypothesis of the study assumes that the optimization of the supply process could increase the stability of the stock formation system and reduce its volume in production.

When constructing a simulation model, it is assumed that:

– the technological process of railroad stations and sections is rational and typical;

– the human factor does not affect the stationarity and efficiency of the transportation process;

– the train schedule is rhythmic throughout the simulation period.

The simulation model was built as a detailed simulation of the turnover of dispatch routes on the railroad network to meet the production needs of the metallurgical enterprise. When devising the model, a hybrid approach is used:

1. To model technological processes of rolling stock turnover, the method of discrete events is used as it corresponds to the essence of technological processes. Each process consists of a set of ordered technological elements. The beginning of each element is the completion of the previous one.

2. To model the process of interaction of various subsystems in a single, complex, multi-phase, and multi-element process, the principle of agent behavior is used.

3. The system dynamics approach and a state diagram with phase transitions were used to model the states of subsystems and elements.

Thus, the specified hybrid approach makes it possible to follow in detail the cause-and-effect relationships between the parameters and states of the system, while ensuring the adequacy of the model as much as possible. The reliability of the results at 95 % (with a probability of relative error $p=0.05$) was ensured by conducting twelve replications with a model time of 9 months [1].

The model was constructed in the AnyLogic University Researcher environment using the Java SE compiler. Model implementation and numerical experimental calculations were performed on a workstation with the following hardware characteristics: 12-Core Intel Xeon E5-2678 v3, 2500 MHz/32608 MB (Registered DDR4 SDRAM) / NVIDIA GeForce RTX 2060 SUPER (8 GB).

5. Results of investigating the process of formation of insurance reserves in the technological system «extraction of raw materials – supply – consumption of raw materials»

5. 1. Results of simulation model development

5. 1. 1. Formalization of the objective function of the optimization problem

Formally, the technological process of supplying raw materials for the needs of metallurgical production can be represented as a set of possible routes, or turnovers of technological dispatch routes on the railroad:

$$T=\{M_i : M_I\}, \quad (1)$$

where M_i is an element of the M_I set of possible options for the turnover of railroad technological routes.

Considering that the whole set of sending routes can be managed and organized centrally, expression (1) can be represented as a set of iron ore and coal (coke) routes:

$$T=\{M_{z,i} : M_{z,ZI} ; M_{v,i} : M_{v,VI}\}, \quad (2)$$

where $M_{z,i} : M_{z,ZI}$ – a subset of routes for transportation of iron ore concentrate; $M_{v,i} : M_{v,VI}$ is a subset of routes for transporting coal (coke).

At the same time, as is known, each turnover of the sender's route is, in most cases, a combination of four components:

$$Q_{M_i} = \sum_{i=1}^{4} t_i, \qquad (3)$$

where t_i are the turnover elements of the sender's route: time spent at the loading station, time in motion from the loading station to the unloading station, time spent at the unloading station, time spent in motion to the loading station, respectively.

The order of the elements in expression (3) is not fundamental since the cyclical process of turnover of the sending route can begin with the movement of the train to the loading station, especially if it concerns the centralized supply of raw materials at the railroad yard. Indeed, if there is a network of suppliers and one recipient in the supply structure, it is logical to choose the destination as the location of the rolling stock. This is due to the fact that in stochastic processes it is not known in what sequence the suppliers will have the cargo ready for shipment.

The actual value of each element in expression (3) in the stochastic process is considered as a random variable with a certain distribution law, which in most cases is determined by the duration of waiting before the execution of technological operations and the actual technological operations themselves. In the implicit expression, the elements of dependence (3) can be represented as follows:

1. The duration of the sending route in an empty state to the loading station:

$$t_{r.por.} = f\left(N_{v.p.s.}; \upsilon_{m.por.}\right), \qquad (4)$$

where $N_{v.p.s.}$ is the volume of the allocated required capacity of the railroad direction on the corresponding rotation route; $\upsilon_{m.por.}$ – route speed of the train in an empty state.

2. The duration of the sending route in a loaded state to the unloading station:

$$t_{r.van.} = f\left(N_{v.p.s.}; \upsilon_{m.van.}\right), \qquad (5)$$

where $N_{v.p.s.}$ is the volume of the allocated required capacity of the railroad direction on the corresponding rotation route; $\upsilon_{m.van}$ – route speed of the train in a loaded state.

3. Duration of finding the warehouse of the sending route at the loading station:

$$t_{st.navan.} = f\left(\lambda_i; N_{skl}; f_{ochik.}\left(\lambda_i, N_{skl}\right); \left\{t_j : t_J\right\}; \left\{t_j : t_J\right\}_{ochik}\right), \qquad (6)$$

where λ_i is the average intensity of cargo mass formation at the i-th point of departure, ton/day; $f_{ochik}(\lambda_i, N_{skl})$ – the waiting time for the batch of empty route cargo to be loaded. This element significantly depends on the ratio of the intensity of accumulation of the cargo lot and its readiness for dispatch with the available (actual) size of the fleet of railroad dispatch routes. N_{skl} – the aggregate value of the fleet of railroad dispatch routes provided to meet the needs for the transportation of raw materials for the relevant metallurgical enterprise; $\{t_j:t_J\}$ – the set of durations of all technological operations for the maintenance of the sending route during its loading, including processing operations at places of non-public use; $\{t_j:t_J\}_{ochik}$ – a set of durations of possible expectations when performing technological operations.

4. Duration of finding the warehouse of the sending route at the unloading station:

$$t_{st.vivan.} = f\left(\left\{t_k : t_K\right\}; \left\{t_k : t_K\right\}_{ochik}\right), \qquad (7)$$

where $\{t_k:t_K\}$ is the set of durations of all technological operations for the service of the sending route when it is loaded, including processing operations at places of non-public use; $\{t_k:t_K\}_{ochik}$ is a set of durations of possible expectations when performing technological operations.

Next, it is necessary to take into account that for the needs of metallurgical production, the simultaneous arrival of sufficient quantities of two types of cargo (enlarged), namely iron ore concentrate (iron ore) and coking coal (coke). So, based on the methods of mathematical logic and the theory of algorithms, sets, and reliability, the probability of technological failure can be formulated in the form of the following inequalities:

1) at least one of the two types of cargo will arrive at the destination before the scheduled time, thereby creating a negative effect of increasing warehouse stocks, i.e.:

$$p\left(t_{norm} - t_{fact}\right)_z \vee p\left(t_{norm} - t_{fact}\right)_v > 0, \qquad (8)$$

where $p(t_{norm}\text{-}t_{fact})_z$ is the probability that a batch of iron ore concentrate will arrive before the regulatory deadline; $p(t_{norm}\text{-}t_{fact})_v$ is the probability that a batch of coking coal will arrive before the set deadline;

2) at least one of the two types of cargo will arrive at the destination later than the planned period, thereby creating a risk of stopping production and creating a critical level of losses for the enterprise, necessary for the restoration of the iron production process:

$$p\left(t_{fact} - t_{norm}\right)_z \vee p\left(t_{fact} - t_{norm}\right)_v > 0, \qquad (9)$$

where $p(t_{fact}\text{-}t_{norm})_z$ is the probability that a batch of iron ore concentrate will arrive later than the standard term; $p(t_{fact}\text{-}t_{norm})_v$ is the probability that a batch of coking coal will arrive later than the set deadline.

It is taken into account that the actual time of arrival of the route with cargo to the destination (t_{fact}), in a cyclical process, is a derivative of the transport-technological model of rotation of railroad routes (1) to (7). Then the objective function of increasing the reliability of the organization of the sending routes can be represented as:

$$\begin{aligned} & p\left(t_{norm} - t_{fact}\right)_z \vee p\left(t_{norm} - t_{fact}\right)_v + \\ & + p\left(t_{fact} - t_{norm}\right)_z \vee p\left(t_{fact} - t_{norm}\right)_v \to \min, \end{aligned} \qquad (10)$$

under constraints:

$$\begin{cases} \psi\left(N_{skl}\right) \to opt, \\ N_{v.p.s.} \le N_{n.p.s.} - \left(N_{vik.p.s.} - \alpha_{rez}\right), \\ \forall N_{skl} \in Z+, \end{cases} \qquad (11)$$

where $\psi(N_{skl})$ is the factor of loading (utilization) of the fleet of sending routes; that is, the use of railroad rolling stock, as the main production resource, in the given production situation and according to the theory of transport processes and systems should be optimal; $N_{n.p.s.}$ – available capacity on the railroad route; $N_{vik.p.s.}$ – allocated capacity of railroads used by other trains; α_{rez} – capacity reserve on this railroad direction.

The specified optimization model (10), (11) is defined by a set of functions represented in an implicit form. The actual implementation of the specified model was performed by us on the basis of simulation (computer) modeling.

5. 1. 2. Development of a simulation model

5. 1. 2. 1. Building the network of agents in the simulation model

To construct a simulation model, the agents given in Table 1 were designed.

Table 1

List and specification of simulation model agents

No. of entry	Name of the agent/population of agents	Functional assignment of an agent/population of agents
1	Main	According to the basic principles of the Java SE compiler, the Main class is the basic class of the software product. The Main agent is the base agent of the simulation model development environment in the Java compiler. This agent ensures the interaction of all other agents of the model
2	Factory	Simulates the technological process of turnover of railway dispatch routes and the interaction of the technological process of a metallurgical enterprise with public rail transport
3	{Suppliers}	The population of agents is «suppliers». Simulates the operation of railway ore and coking coal dispatch points for the needs of a metallurgical enterprise. The specified population forms a network of supply points on the rotation range of the sending railway routes
4	{Train}	Population of «railway route» agents. Simulates the use of railway rolling stock (specialized cars and locomotives). The specified population forms the main production resource of the process of supplying raw materials for the needs of the metallurgical enterprise
5	{Order}	A population of «order» type agents. Simulates the occurrence and satisfaction of information about the availability of transportation requests. This population is used as an information message that follows the cargo during the entire transportation stage
6	factoryProcess	Agent «factory». Simulates the technological line of intensity of consumption by the metallurgical process of raw materials supplied by railway routes

The population of agents is created in such a way as to reflect the main elements of the transport and technological supply chain of raw materials for metallurgical production. Subsequently, they will be used when performing simulations.

5. 1. 2. 2. Setting up the simulation model database

For the convenience of managing data arrays, all source information is summarized in tabular forms. Thus, data on dispatch stations on the iron ore and coal networks with dispatch intensities and variation characteristics are given in Table 2.

In Table 2, in the «typeCargo» column, the identifier «1» corresponds to the cargo «iron ore», the indicator «2» corresponds to the cargo «coking coal». The «average» and «deviation» columns indicate the average and standard deviation of a sample of daily volumes of cargo arriving from the respective departure stations.

Table 3 specified parameters of the process of consumption of raw materials in production. Similarly, with the identification of Table 2, in the «typeCargo» column, the identifier «1» corresponds to the cargo «iron ore», the indicator «2» corresponds to the cargo «coking coal».

Table 2

Database on the intensities of the formation of cargo flows at iron ore and coking coal dispatch stations

Station	average	deviation	typeCargo
Terny	6,903	2,887	1
Dniprorudne	5,607	1,864	1
Ryadova	5,408	2,025	1
Inhulets	4,733	1,687	1
Kryvyy Rih	3,917	796	1
Hrekuvata	3,339	2,383	1
Dnipro	594	244	1
Zaporizhzhya-Kam'yans'ke	480.3	437.8	2
Avdyeyevka	2,680.6	810.2	2

Table 3

Database on intensities of consumption of raw materials in metallurgical production

average	deviation	typeCargo
30.501	11.886	1
3.160.9	1.248	2

The database is stored in any spreadsheet program (such as MS Excel). This approach makes it possible to simplify the process of setting initial parameters regarding the formation of a network of suppliers and the capacity of cargo flows of raw materials.

5. 1. 2. 3. Setting up agents

Agent population settings {Suppliers}.

The population of agents {Suppliers} forms cargo flows of raw materials for the needs of metallurgical production. The main task of these agents is to form an order for the shipment of consignments on the selected network of suppliers. The general view of the {Suppliers} population agent in the AnyLogic environment is shown in Fig. 1.

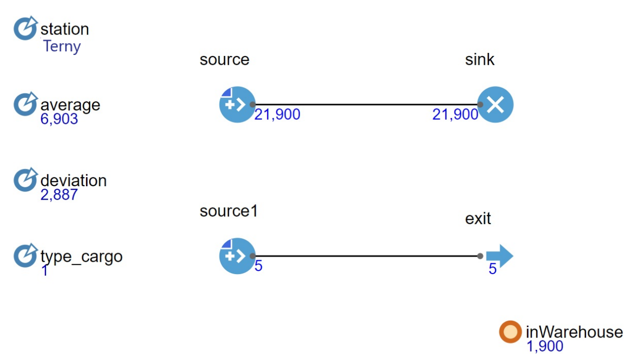

Fig. 1. General view of the population agent {Suppliers} in the AnyLogic University Researcher (USA) environment

In each agent of the {Suppliers} population from the model database (chapter 5.2), the following is formed:

– binding to the area in the GIS space – the Station parameter;

– the average value (average) and standard deviation (deviation) of the daily volume of cargo sent from the corresponding station to the metallurgical enterprise, t;

– type of cargo generated by this agent (type_cargo=1 – iron ore concentrate, type_cargo=2 – coking coal).

Thus, the key element in the functioning of these agents is the generators of random variables forming the flow, according to the density of the distribution of daily volumes. The random variable generator generates a stream of demands, where each demand corresponds to a ton of cargo arriving at the destination. Upon receipt of each request to the storage device, the algorithm shown in Fig. 2 is implemented.

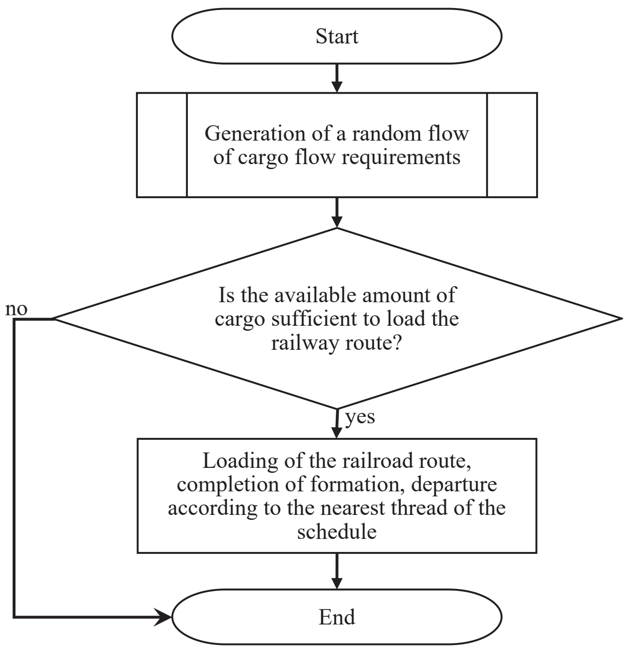

Fig. 2. Block diagram of the algorithm for generating information messages about the presence of a ready-to-ship consignment

This algorithm provides for the dispatch of railroad routes upon the fact of accumulation to the norm of mass. After fulfilling the condition regarding the availability of the required batch of cargo before shipment, the generation of a corresponding information message is enabled, containing data on:

1) point (station) of departure;
2) cargo volume (number of tons);
3) type of cargo (ore or coal).

Thus, the generator of random source requirements, respectively, of the output data generates (by default – according to the normal distribution law) the receipt and accumulation of consignments of goods for their dispatch. When the mass is accumulated to the norm, a new message is generated about the readiness to send the formed batch of cargo (Fig. 3).

This message is transmitted to the source block, where the population agent {Order} is identified (Table 3) – it is matched with information about the departure station, the type of cargo, and the moment of formation of the cargo batch to the rate of loading on the sending route. Next, the specified agent is transferred to the main agent of the technological process of the model – the Factory agent (Fig. 4).

Further experiments with the model showed that the specified approach allows adequately simulating the process of cargo accumulation to the mass norm on the supply network of various types of raw materials for the needs of metallurgical production.

```
«inWarehouse++;

if (inWarehouse >= main.trainCapacity){

    Order orderForDeparture = new Order ( );

    orderForDeparture.suppliersOrder = station;

    source1.inject(1);

    inWarehouse -= main.trainCapacity;
}»
```

Fig. 3. Text of the message about the readiness of the consignment for shipment

```
«agent.suppliersOrder = station;

agent.cargo = type_cargo;

agent.timeIn = time();

main.factory.enter.take(agent);»
```

Fig. 4. Text of the message about the identification of the population agent {Order}

Setting up the Factory agent.

After the formation of a new message about the readiness to send a batch of cargo, the {Order} population agent is transferred to the Factory agent. The specified agent simulates the technological process of the turnover of dispatch routes on the railroad network, the interaction of the technological process of the metallurgical enterprise with the railroad transport of general use and raw material supply points. In essence, this agent simulates the functioning of the transport and technological system «supply – transportation – production», thereby defining the turnover of the sending routes precisely as technological, organized according to the features of the production technology of the metallurgical enterprise.

The model built implements the approach of centralized management of the fleet of railroad routes. That is, the same fleet of cars is used for transporting ore and iron ore concentrate and coking coal. Therefore, the main element of the process is waiting for rolling stock free for loading. The algorithm of this process is shown in Fig. 5.

All transportation orders are formed in a single queue and are gradually implemented by a centralized fleet of freight trains. After the appearance of a free train, the route in an empty state goes to the cargo departure station, where the route is loaded. Then, the loaded train goes to the destination station, where it is unloaded. If there are no applications for transportation, empty routes are at the station of the route base (Zaporizhia-Live station) waiting for transportation work. Thus, when using this approach, the following principles of organization of sending (technological) routes are implemented:

– centralized management of the fleet of dispatch routes;

– consideration of cargo expectations and free railroad routes;

– a systematic approach in the transport and technological system «network of suppliers – railroad routes – production».

The algorithm shown in Fig. 5 can be implemented based on the discrete-event approach (Fig. 6).

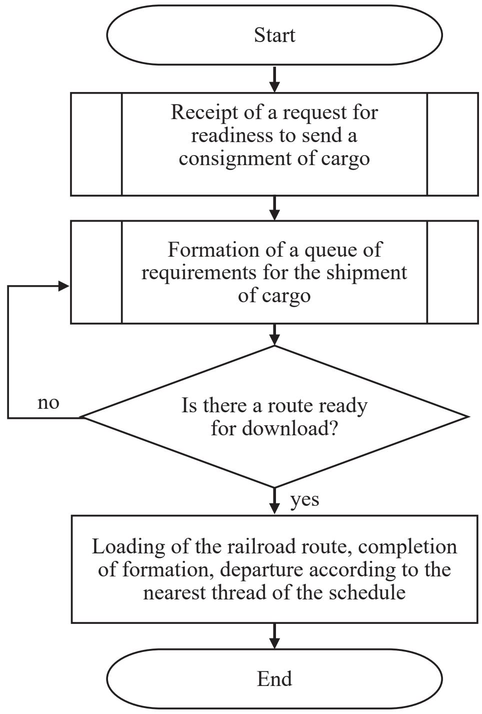

Fig. 5. Block diagram of the algorithm for generating information messages about the presence of a ready-to-ship consignment

A request (order) for the transportation of cargo, which is transmitted from the population agent {Suppliers} to the element of forming a queue from orders (seize block). In this block, all orders for transportation are formed in a single queue and await the free composition of the railroad route. If there are free railroad routes, the resource is «captured» – a railroad route (trains block) with a sequential simulation of the turnover of the railroad route:

– moveToSupply – duration of train movement to the loading station, hours;

– loading – length of stay of the railroad route at the loading station, hours;

– moveTo – the duration of the train movement to the unloading station, hours;

– Unloading – length of stay of the railroad route at the unloading station, hours.

The turnover of dispatch routes is carried out at the railroad yard with a network of dispatch points. Accordingly, with each seizure of a resource (free stock of a railroad route), the parameter of the cargo departure station is transferred from the population agent {Suppliers} to the parameters of the selected {Traine} population agent (Fig. 7). This is how the traffic management of technological (dispatch) routes on the railroad network is simulated.

When the cargo arrives at the unloading points, the formation of ore and coke reserves is simulated. At the output of each requirement from the Unloading block (Fig. 6) with the help of Java code (Fig. 8), the corresponding algorithm for the formation of raw material stocks is implemented (Fig. 9).

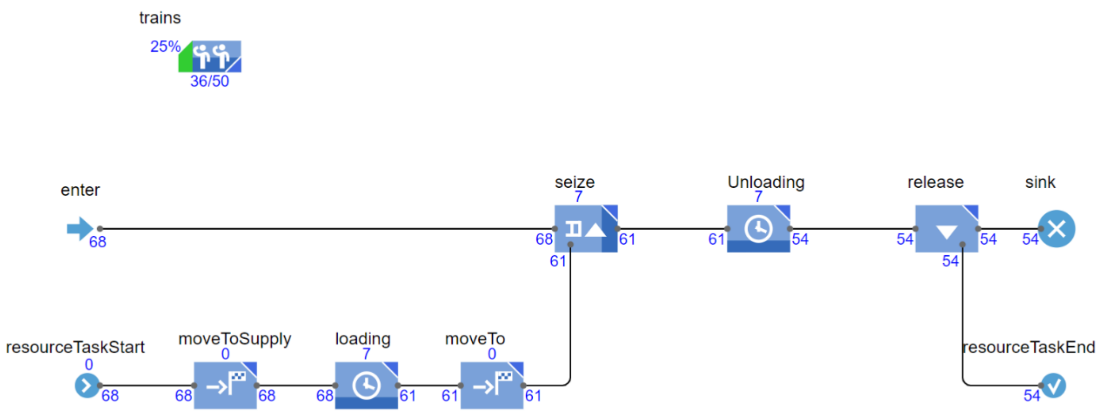

Fig. 6. Discrete-event diagram of the turnover process of shipping routes with raw materials in the AnyLogic environment

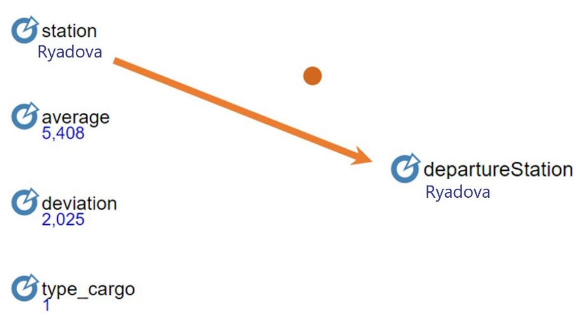

Fig. 7. Discrete-event diagram of the turnover process of the railroad dispatch routes:
a – population agent {Suppliers}; *b* – population agent {Train}

```
«if (agent.cargo == 1) oreDelivInWarehouse += main.trainCapacity;
if (agent.cargo == 2) coaDelivlInWarehouse += main.trainCapacity;»
```

Fig. 8. Java code for the implementation of the algorithm for the formation of raw material stocks at the unloading point

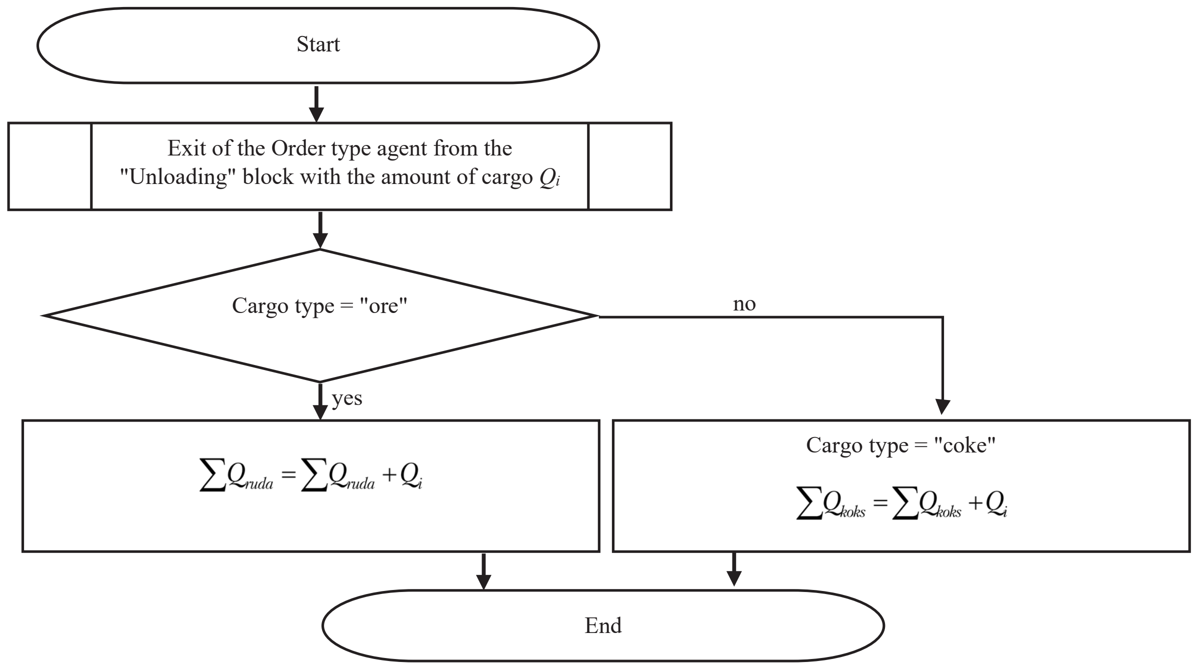

Fig. 9. Algorithm for the formation of production stocks at a metallurgical enterprise after the arrival of railroad routes

Thus, moving through the stages of the algorithm (Fig. 9), and applying the created populations of agents at individual steps, the process of stock formation is modeled, and the performance indicators of the transport-technological line are determined.

5. 1. 2. 4. Results of the implementation of the simulation model

In the course of the research, a series of experiments was performed with the developed simulation model based on the basic parameters of the transport and technological supply line of iron ore concentrate and coke, typical of 2021 (Table 4).

The period of 2020–2022 was a peak period for economic activity on the territory of modern Ukraine, so modeling will be carried out for peak loads for the railroad transport network.

5. 2. Establishing the regularity of formation of insurance reserves

Based on analysis of the results of a series of experiments, it was established that the optimal fleet of railroad routes is 30 units at a load of 65 %. The average (estimated) stock levels of iron ore concentrate and coke at production in the amount of 16,770 tons (Fig. 10) and 18,558 tons (Fig. 11), respectively, were used in the modeling. For such initial data, the variation of raw material stock volumes during the entire simulation period is quite significant: 26 % for ore and 9.5 % for coke (Fig. 12).

These results are explained by the significant branching of the supply network of iron ore concentrate and multiple parameters of the routes along the technological routes with iron ore.

Table 4

Values of the initial parameters for the basic modeling of the process of supplying iron ore concentrate and coke for the needs of PAT Zaporizhstal

No. of entry	Parameter ID	Measurement unit	Value	Note
1	Intensity of formation of cargo flows	t/24 h	Table 1	The flow is the simplest, Poisson
2	Intensity of consumption of raw materials: – iron ore concentrate; – coke	t/24 h	30,501.0; 3,160.9	The flow is the simplest, Poisson
3	Mass norm of the dispatching (technological) route	t	4,000.0	Permanent
4	Schedule of technological routes	–	–	Accidental, due to the fact of the accumulation of cargo up to the norm of the mass of the warehouse
5	Railroad route warehouse fleet management	–	–	Centralized. Each wagon can be used to transport both ore and coal
6	Length of stay at departure station: mean standard deviation	hour	23; 0.17 $M(x)$	Normal distribution
7	Length of stay at destination station: mean standard deviation	hour	23; 0.17 $M(x)$	Normal distribution
8	Route speed	km/h	37	Permanent
9	Duration of locomotive equipment at turnover stations: mean standard deviation	hour	1; 0.17 $M(x)$	Normal distribution

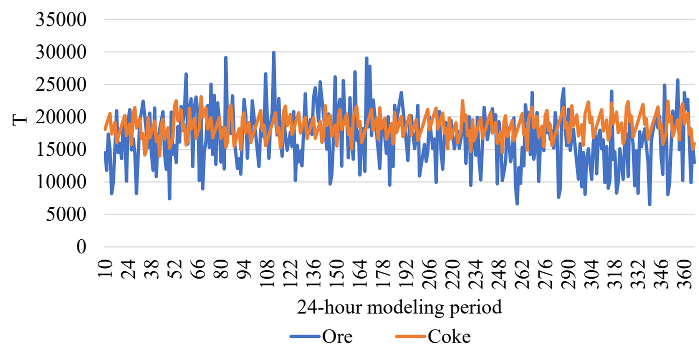

Fig. 10. Chart of fluctuations in iron ore and coke reserves in the organization of supply by railroad technological routes (within a year of model time)

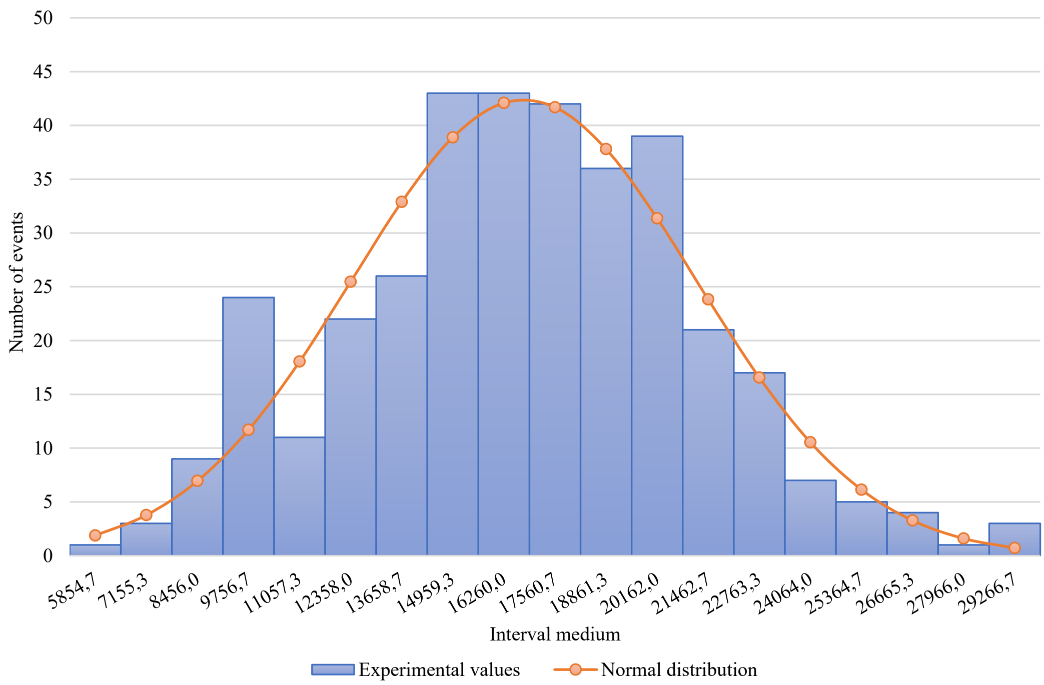

Fig. 11. Density of the distribution of the volume of iron ore reserves (at the end of each day) during the year

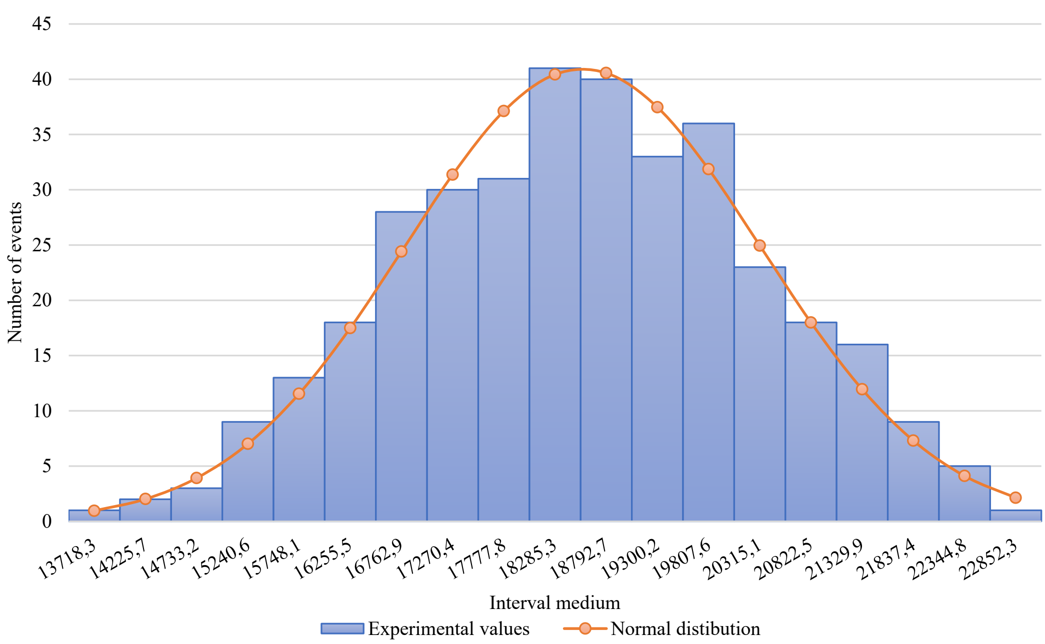

Fig. 12. Density of the distribution of the volume of coke reserves (at the end of each day) during the year

Then, according to the objective function of the optimization model (10) and its constraints (11), the minimum deviations with the given modeling parameters (Table 4) are as follows (Table 5).

Table 5

The range of fluctuations in the supply of raw materials during the organization of supply by shipping routes

Stock type	Standard deviation per day, t	+/–σ(x) (68.26 %)	+/–2σ(x) (95.45 %)	+/–3σ(x) (99.73 %)
Iron ore concentrate	4,372	–4,372	–8,743	–13,115
		+4,372	+8,743	+13,115
Coke	1,766	–1,766	–3,532	–5,298
		+1,766	+3,532	+5,298

Thus, it can be seen that even for an accuracy of 99.73 %, the volume of fluctuations in raw materials is only a small fraction of the total volume of production stocks and the available capacity of the company's warehouses. Accordingly, regulation within such volumes is quite a real task.

6. Discussion of results based on the study of formation processes

The simulation model built simulates the full technological cycle of the rotation of technological railroad routes on the real network using global positioning technology (GIS maps) (Fig. 6) and the dynamic change of tracking routes, depending on the intensity of the accumulation of cargo mass (Fig. 1–5). This simulation technique was implemented through a combination of agent and discrete-event approaches (Fig. 6).

As a result, the main feature and advantage of the presented simulation model is the simultaneous simulation of the entire transport-technological system «extraction of raw materials – supply – consumption of raw materials», which allowed us to combine three technological processes into one transport-technological system (Fig. 6–9). At the same time, the model built is not a fundamentally new way of modeling and is a further development of the methodology of network planning and redistribution of production resources on the network of points of departure and destination of cargo.

In contrast to classical tools of linear, stochastic, or integer modeling [3, 5, 25], the scale of modeling is fundamentally new in our model. The model significantly expands the boundaries of the system under investigation. At the same time, elements of technological cycles and a stochastic approach were taken into account in the distribution of the duration of operations, such as waiting time, non-matching, loading.

As a result of a series of experiments with the model, according to the open data from PAT Zaporizhstal in 2021, it was possible to establish the degree of fluctuation in the insurance stock of the metallurgical enterprise in the system «raw material extraction – supply – production» (Fig. 11, 12, Table 5). It has been proven that the density of the stock distribution is subject to the normal theoretical distribution. This once again confirms the hypothesis about the naturalness of the specified process [1, 11, 15], which must be taken into account when planning the production activities of all participants in the specified process.

Since the process of forming the insurance reserve is a random process, conducting a series of experiments with the developed simulation model turned out to be very convenient to use. The results of the experiments provide a visual and convenient practical tool for assessing the limit values of fluctuations, i.e., risks. The availability of such a tool is critically important when planning the supply of metallurgical enterprises. For example, with the estimated size of the fleet of railroad routes at the specified turning range of 30 units (degree of utilization 65 %), it was established that the volumes of iron ore concentrate fluctuated (Fig. 11, 12, Table 5) as follows:

– for 2-sigma (95.45 % of all possible cases): (–8743 tons; +8743 tons);

– for 3-sigma (99.73 % of all possible cases): (–13115 tons; +13115 tons).

For coke:

– for 2-sigma (95.45 % of all possible cases): (–3532 tons; +3532 tons);

– for 3-sigma (99.73 % of all possible cases): (–5298 tons; +5298 tons).

However, our results are valid only for «non-distributive» systems, that is, in systems with one recipient. For multi-recipient processes, other approaches are needed, including priority criteria and algorithms for distribution of supply routes.

In addition, according to the results of the construction of the simulation model, it was not possible to take into account the cost of delivering goods and conduct a systematic factor analysis of effectiveness in the implementation of the «rigid traffic schedule» of technological routes. Thus, the study of the effectiveness of the «rigid traffic schedule» is relevant and a priority in the future.

7. Conclusions

1. With the help of an optimization model, the process of rotation of dispatch routes at a railroad yard with multiple suppliers and one consignee has been formalized. In contrast to existing ones, our optimization model takes into account the centralized management of the fleet of railroad dispatch routes, and the minimum deviations of fluctuations in iron ore concentrate and coke stocks were chosen as the optimization criterion. Since most of the elements of the objective function of the model are represented in an implicit form, the model was implemented using simulation modeling methods. For this purpose, a simulation model was built, based on discrete-event and agent approaches in the AnyLogic University Researcher environment, by using Oracle libraries and the Java SE compiler. The model takes into account stochastic processes and centralized management of vehicle fleets in the technological system «raw material extraction – supply – consumption of raw materials».

Thus, the simulation model built makes it possible to systematically determine the need for rolling stock and, at the same time, the level of fault tolerance of the technological supersystem «raw material extraction – raw material supply network – production».

2. Based on the analysis of modeling results using the open data from PAT Zaporizhstal in 2021, it was determined that the optimal size of the fleet of railroad routes on the specified rotation polygon is 30 units. The utilization rate

is 65 %. Fluctuations in raw material stocks have a «natural character», which is confirmed by the normal distribution of the density of stock volumes with a standard deviation of the indicator:

– for volumes of supply of iron ore concentrate: $\sigma(x)=\pm 4372$ tons;

– for coke volumes: $\sigma(x)=\pm 1766$ tons.

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.

Funding

The study was conducted without financial support.

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.

References

1. Matsiuk, V. (2017). A study of the technological reliability of railway stations by an example of transit trains processing. Eastern-European Journal of Enterprise Technologies, 1 (3 (85)), 18–24. https://doi.org/10.15587/1729-4061.2017.91074
2. Parida, P. (2014). Unlocking Mineral Resource Potential in Southern African Countries: Is Rail Infrastructure up to the Challenge? Transportation Research Procedia, 1 (1), 206–215. https://doi.org/10.1016/j.trpro.2014.07.021
3. Vaezi, A., Verma, M. (2017). An analytics approach to dis-aggregate national freight data to estimate hazmat traffic on rail-links and at rail-yards in Canada. Journal of Rail Transport Planning & Management, 7 (4), 291–307. https://doi.org/10.1016/j.jrtpm.2017.12.001
4. Grushevska, K., Notteboom, T., Shkliar, A. (2016). Institutional rail reform: The case of Ukrainian Railways. Transport Policy, 46, 7–19. https://doi.org/10.1016/j.tranpol.2015.11.001
5. Gupta, D., Dhar, S. (2022). Exploring the freight transportation transitions for mitigation and development pathways of India. Transport Policy, 129, 156–175. https://doi.org/10.1016/j.tranpol.2022.10.013
6. Guglielminetti, P., Piccioni, C., Fusco, G., Licciardello, R., Musso, A. (2017). Rail Freight Network in Europe: Opportunities Provided by Re-launching the Single Wagonload System. Transportation Research Procedia, 25, 5185–5204. https://doi.org/10.1016/j.trpro.2018.02.047
7. Crozet, Y. (2017). Rail freight development in Europe: how to deal with a doubly-imperfect competition? Transportation Research Procedia, 25, 425–442. https://doi.org/10.1016/j.trpro.2017.05.420
8. Bouraima, M. B., Qiu, Y., Yusupov, B., Ndjegwes, C. M. (2020). A study on the development strategy of the railway transportation system in the West African Economic and Monetary Union (WAEMU) based on the SWOT/AHP technique. Scientific African, 8, e00388. https://doi.org/10.1016/j.sciaf.2020.e00388
9. Skoczylas, A., Stefaniak, P., Gryncewicz, W., Rot, A. (2023). The Concept of an Intelligent Decision Support System for Ore Transportation in Underground Mine. Procedia Computer Science, 225, 922–931. https://doi.org/10.1016/j.procs.2023.10.079
10. Katsman, M. D., Matsiuk, V. I., Myronenko, V. K. (2023). Modeling the reliability of transport under extreme conditions of operation as a queuing system with priorities. Reliability: Theory & Applications, 2 (73), 167–179. https://doi.org/10.24412/1932-2321-2023-273-167-179
11. Matsiuk, V., Opalko, V., Savchenko, L., Zagurskiy, O., Matsiuk, N. (2023). Optimisation of transport and technological system parameters of an agricultural enterprise in conditions of partial uncertainty. Naukovij Žurnal «Tehnika Ta Energetika», 14 (3), 61–71. https://doi.org/10.31548/machinery/3.2023.61
12. Anufriyeva, T., Matsiuk, V., Shramenko, N., Ilchenko, N., Pryimuk, O., Lebid, V. (2023). Construction of a simulation model for the transportation of perishable goods along variable routes. Eastern-European Journal of Enterprise Technologies, 2 (4 (122)), 42–51. https://doi.org/10.15587/1729-4061.2023.277948
13. Karmanesh, Y., Bagheri, M., Mohammad Hasany, R., Saman Pishvaee, M. (2024). Two-stage stochastic programming approach for fleet sizing and allocating rail wagon under uncertain demand. Computers & Industrial Engineering, 188, 109878. https://doi.org/10.1016/j.cie.2023.109878
14. Michal, G., Huynh, N., Shukla, N., Munoz, A., Barthelemy, J. (2017). RailNet: A simulation model for operational planning of rail freight. Transportation Research Procedia, 25, 461–473. https://doi.org/10.1016/j.trpro.2017.05.426
15. Prokhorchenko, A., Parkhomenko, L., Kyman, A., Matsiuk, V., Stepanova, J. (2019). Improvement of the technology of accelerated passage of low-capacity car traffic on the basis of scheduling of grouped trains of operational purpose. Procedia Computer Science, 149, 86–94. https://doi.org/10.1016/j.procs.2019.01.111
16. Tang, X., Jin, J. G., Shi, X. (2022). Stockyard storage space allocation in large iron ore terminals. Computers & Industrial Engineering, 164, 107911. https://doi.org/10.1016/j.cie.2021.107911
17. Song, L., Yu, L., Li, S. (2023). Route optimization of hazardous freight transportation in a rail-truck transportation network considering road traffic restriction. Journal of Cleaner Production, 423, 138640. https://doi.org/10.1016/j.jclepro.2023.138640

18. Okorokov, A. (2015). Development of techniques to optimize the technical parameters of transport cargo complexes. Eastern-European Journal of Enterprise Technologies, 2 (3 (74)), 9–14. https://doi.org/10.15587/1729-4061.2015.39792
19. Ren, Q., Xu, M. (2024). Injury severity analysis of highway-rail grade crossing crashes in non-divided two-way traffic scenarios: A random parameters logit model. Multimodal Transportation, 3 (1), 100109. https://doi.org/10.1016/j.multra.2023.100109
20. Schöbel, A., Aksentijevic, J., Stefan, M., Blieberger, J. (2017). Optimization of rail traffic flow using Kronecker algebra during maintenance on infrastructure. Transportation Research Procedia, 27, 545–552. https://doi.org/10.1016/j.trpro.2017.12.040
21. Matsiuk, V., Galan, O., Prokhorchenko, A., Tverdomed, V. (2021). An Agent-Based Simulation for Optimizing the Parameters of a Railway Transport System. Proceedings of the 17th International Conference on ICT in Education, Research and Industrial Applications. Integration, Harmonization and Knowledge Transfer. Volume I: Main Conference. https://ceur-ws.org/Vol-3013/20210121.pdf
22. Kozachenko, D., Vernigora, R., Balanov, V., Berezovy, N., Yelnikova, L., Germanyuk, Y. (2016). Evaluation of the Transition to the Organization of Freight Trains Traffic By the Schedule. Transport Problems, 11 (1), 41–48. https://doi.org/10.20858/tp.2016.11.1.4
23. Namazov, M., Matsiuk, V., Bulgakova, I., Nikolaienko, I., Vernyhora, R. (2023). Agent-based simulation model of multimodal iron ore concentrate transportation. Naukovij Žurnal «Tehnìka Ta Energetika», 14 (1). https://doi.org/10.31548/machinery/1.2023.46
24. Bulakh, M., Okorokov, A., Baranovskyi, D. (2021). Risk System and Railway Safety. IOP Conference Series: Earth and Environmental Science, 666 (4), 042074. https://doi.org/10.1088/1755-1315/666/4/042074
25. Panchenko, S., Prokhorchenko, A., Dekarchuk, O., Gurin, D., Mkrtychian, D., Matsiuk, V. (2020). Development of a method for studying the impact of the time reserve value on the reliability of the train schedule based on the epidemiological SIR model. IOP Conference Series: Materials Science and Engineering, 1002 (1), 012016. https://doi.org/10.1088/1757-899x/1002/1/012016
26. D'Ariano, A., Meng, L., Centulio, G., Corman, F. (2019). Integrated stochastic optimization approaches for tactical scheduling of trains and railway infrastructure maintenance. Computers & Industrial Engineering, 127, 1315–1335. https://doi.org/10.1016/j.cie.2017.12.010
27. Pashchenko, F. F., Kuznetsov, N. A., Ryabykh, N. G., Minashina, I. K., Zakharova, E. M., Tsvetkova, O. A. (2015). Implementation of Train Scheduling System in Rail Transport using Assignment Problem Solution. Procedia Computer Science, 63, 154–158. https://doi.org/10.1016/j.procs.2015.08.326
28. Yi, X., Marlière, G., Pellegrini, P., Rodriguez, J., Pesenti, R. (2023). Coordinated train rerouting and rescheduling in large infrastructures. Transportation Research Procedia, 72, 319–326. https://doi.org/10.1016/j.trpro.2023.11.410
29. Samà, M., Meloni, C., D'Ariano, A., Corman, F. (2015). A multi-criteria decision support methodology for real-time train scheduling. Journal of Rail Transport Planning & Management, 5 (3), 146–162. https://doi.org/10.1016/j.jrtpm.2015.08.001
30. Gupta, P., Bazargan, M., McGrath, R. N. (2003). Simulation model for aircraft line maintenance planning. Annual Reliability and Maintainability Symposium. https://doi.org/10.1109/rams.2003.1182020
31. Secchi, D., Grimm, V., Herath, D. B., Homberg, F. (2024). Modeling and theorizing with agent-based sustainable development. Environmental Modelling & Software, 171, 105891. https://doi.org/10.1016/j.envsoft.2023.105891
32. Hoffmann, T., Ye, M., Zino, L., Cao, M., Rauws, W., Bolderdijk, J. W. (2024). Overcoming inaction: An agent-based modelling study of social interventions that promote systematic pro-environmental change. Journal of Environmental Psychology, 94, 102221. https://doi.org/10.1016/j.jenvp.2023.102221
33. Achter, S., Borit, M., Cottineau, C., Meyer, M., Polhill, J. G., Radchuk, V. (2024). How to conduct more systematic reviews of agent-based models and foster theory development – Taking stock and looking ahead. Environmental Modelling & Software, 173, 105867. https://doi.org/10.1016/j.envsoft.2023.105867