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INCREASING THE EFFICIENCY OF OPERATION AND MANAGEMENT OF RAILROAD TRANSPORT INFRASTRUCTURE BASED ON MAXIMUM LEVELS OF FAULT TOLERANCE

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This paper considers the optimization of parameters for a railroad transport system. The maximum level of technological reliability and the average time spent by trains on the route are used as optimization criteria. The purpose of the study is to establish the optimal parameters for the operational process of railroad transport systems according to the criterion of the maximum level of technological reliability and the minimum time of trains on the route. Methods of technological reliability research have been proposed. Taking into account that the entire technological process is a sequential set of technological elements, a simulation model of the technological process of the transit transport-technological line along a route direction has been built. A population of agents that simulates the operation of railroad sections of the rotation of train locomotives and is a key subsystem of the simulation model has been developed and configured. The simulation model makes it possible to optimize the parameters of multi-section railroad lines. This approach is provided owing to the agent approach. As a result of the experiments, the optimal parameters of the functioning of railroad lines were established when organizing the passage of transit trains. The coefficient of utilization of the locomotive fleet fluctuates within the optimal range (0.55–0.65), which indicates the sufficiency of traction resources in the railroad system. The optimal parameters of the railroad transport system were established experimentally using the example of a train flow of 85 pairs of trains on a two-track route with five sections. The problem of "abandoned trains" has a solution but, to this end, it is necessary to increase the fleet of train locomotives by 150–200 % relative to existing standards. At the same time, even with an unlimited fleet of train locomotives, there is a fairly high probability (up to 30–50 %) of technological failures

Keywords: technological reliability, railroad transport system, rolling stock, simulation modeling, discrete-event simulation

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1. Introduction

Railroad transport systems represent a fairly complex and specific integrated complex, which consists of a number of mass service systems (MSSs) of different nature. Most of these MSSs have a limited number of service channels and queuing sets, and very importantly, extremely limited ability to regulate and manage the MSS's queuing and channel requirements. For example, the track development of railroad stations, where the number of tracks is essentially a limited number of service channels, can be changed only after a complete reconstruction of the track infrastructure of stations. Another example is that interstation sections have a limited capacity, which is also almost impossible to increase at once.

At the same time, the organization of train traffic on railroad routes is a rather complex and large technological system, which includes a set of various MSSs. When these MSSs interact, there are delays, waiting, technological failures in the process, as well as the phenomenon of "abandoned" trains.

On the one hand, the above negative phenomena can be considered a mandatory element of such complex technological processes. On the other hand, reducing their impact on the technological transport process would significantly increase the efficiency of the train traffic management system, especially in terms of its fault tolerance. Therefore, scientific and applied research aimed at evaluating the efficiency of railroad lines according to a single, systematic criterion of technological failure resistance is relevant.

2. Literature review and problem statement

Ensuring the reliability of technical systems remains a fairly relevant issue for the transport industry. For railroad transport, reliability is, as a rule, considered as an element of normalizing parameters of the operational process. At the same time, the optimization of transport and technological processes can be carried out according to various criteria.

Study [1] reports the results of the assessment of suburban railroads integrated into the city infrastructure. Analysis of the results is carried out by comparing classic indicators of transport efficiency and the conditions of safe movement of passengers along with the transport infrastructure. The approach is new, but the authors do not justify the choice and feasibility of comparing indicators of different technological nature.

As a result of the optimization of the carbon emission rate, in study [2] the authors managed to build a model for a significant reduction of CO_2 emissions during the operation of railroad transport. At the same time, the basis of modeling is based on classic technical and operational indicators of railroad work: productivity and carrying capacity, which cannot be considered fundamentally new in operational science. In contrast, in work [3] on a similar environmental topic, the authors suggest minimizing the negative impact on the ecosystem through the introduction of new indicators: operational KPI and USI survey. At the same time, the authors almost do not take into account the technological features of rail transport, such as the train schedule and the large mass of rolling stock containers.

In studies [4], optimization models are given, in which the criterion is the maximum level of fault tolerance of transport systems. The approach is new from the point of view of evaluating the technological reliability of transport; however, the authors do not take into account the peculiarities of different transport systems and consider the process as a multifactor mass service system.

In works [5, 6], it is proposed to increase the efficiency of transport operation through the improvement of power systems by introducing intelligent technologies. Work [5] devised a criterion for the efficiency of the "engine driver-locomotive" energy system during operation. It is a ratio of various efficiency indicators that reflect various properties of the system. The evaluation of train control efficiency by several criteria is quite difficult to formalize by means of classical mathematics. Therefore, to record not only quantitative but also qualitative characteristics of the activity of a locomotive driver or an intelligent decision support system, it is suggested to use the fuzzy logic methods given in [6]. Qualitative control characteristics are formalized using the theory of fuzzy sets, by defining separate membership functions for each parameter. This approach makes it possible to assess the degree of influence of the human operator on the quality of control but needs to be developed to determine the fault tolerance of the railroad transport infrastructure as a whole.

Normalization itself in practice is mostly carried out by analytical methods and involves the effective functioning of ZTS within the confidence intervals of the corresponding calculated optimums [7]. However, this approach cannot ensure the proper level of trouble-free operation of transport systems, as it does not take into account the possibility of exceeding standards due to fluctuations in the volume of transport work, especially over a long planning horizon [8].

The objective complexity of conducting research on the reliability of technological transport systems is its complexity and scale. A significant set of initial parameters, their stochastic nature, and the dynamism of the process in general call into question the feasibility of using analytical models [9]. In most cases, the probability of failure and the duration of trouble-free operation of technical systems can be determined only experimentally, by conducting complex and expensive tests of the samples themselves (for technical objects) or models [10].

Many researchers try to study multiphase technological processes by exploring individual components of the technological process, which does not make it possible to establish the overall level of reliability: the number of system states can exceed tens of thousands and greatly complicates (and even makes impossible) calculations. Therefore, against the background of the above, simulation methods can be one of the few research tools of complex, multiphase technological processes of railroad transport [11]. At the same time, when modeling complex, multiphase supply chains, individual researchers face the problem of modeling the consistency of transport and technological processes of various elements in one system [12], considering each sub-process separately. The results of such studies cannot provide adequate reliability since the system is lost in the assessment of the entire process.

In [13], the authors use a fairly modern and powerful computer simulation tool – the agent approach. This methodology makes it possible to simulate the entire process at once, thus providing a system analysis. However, in the work itself, the authors failed to fully apply the agent approach due to the high abstractness of the model.

In a significant number of scientific studies, the concept of risk is used as the main criterion of reliability, which, according to the authors, is not a sufficiently successful category precisely in assessing the reliability of processes and systems [14]. Moreover, risk is often understood precisely as the probability of failure, which contradicts the existing international standards for the reliability of equipment and technologies, and the general principles of the theory of reliability.

Taking into account the above, it can be argued that the study of the reliability of technological processes of railroad lines as large and complex systems was not carried out enough. Moreover, the indicator of the probability of refusal to accept trains is used in practice, as a rule, only when assessing the accuracy of the execution of the traffic schedule [15]. The lack of methods for assessing the reliability of the technological processes of railroad stations does not make it possible to determine the objective level of failure of timely reception and timely departure of trains, which greatly complicates the development of norms for the effective interaction of elements in the railroad transport system.

3. The aim and objectives of the study

The purpose of our study is to establish the optimal parameters for the operational process of railroad transport systems according to the criterion of the maximum level of technological reliability and the minimum time of trains on the route. This will make it possible to obtain a model that would make it possible to optimize the parameters of multi-section railroad routes and could become a theoretical justification for increasing the efficiency of operation and management of railroad infrastructure based on limit levels of fault tolerance.

To achieve the goal, the following tasks were set:

– to develop a simulation model of the operational process of the transit line on the railroad route;

– to implement the optimization model of the operational process of the transit line on the railroad route according to the criterion of the limit level of technological failure resistance; the problem of "abandoned trains" was additionally studied.

4. The study materials and methods

The object of our study is the technological process of transit transport and technological lines of railroads.

The main hypothesis of the study assumes that the limit level of technological failure resistance of transit transport and technological lines of railroads requires a different set of technological parameters than the existing one.

When developing a simulation model, it is assumed that:

– the technological process is typical, rational, rhythmic;

– there are no external factors that negatively affect the efficiency of the technological process;

– the duration of elements of technological processes, elements of turnover of train locomotives and freight cars is random. The density of the distribution of random variables is known;

– the length of the turning sections and the number of interstation runs with intermediate stations are typical for the railroad network of Ukraine;

– the first and last technical stations are forming and unforming stations for even and odd car flows. Intermediate technical stations are transit technical stations;

– incoming car flows of even and odd directions are the simplest;

– the train schedule is rational and rhythmic.

The simulation model was built as a computer simulation of the turnover of train locomotives of transit freight traffic on the n-th number of rotation stations. When developing the model, the principles of object-oriented programming were used, in which each element was represented as a separate class (agent) with a certain set of parameters and functions.

The model was tested in the AnyLogic Universiyu Rescher environment with Java SE on the hardware resources of the Alfa Server #209 Core i7-9700 research workstation, 64 GB RAM, NVIDIA Quadro RTX A4000 16 GB.

5. Results of investigating the operational process of railroad transport systems according to the criterion of the limit level of technological reliability

5. 1. Results of simulation model development

The transit transport and technological line in railroad transport is a complex and large closed system. When studying such a large object, it is difficult to establish the necessary methodology. One of the few such tools is computer simulation, which will be used as a basic methodology for solving a scientific and applied problem.

However, with all the variety of simulation methods, it is not always possible to achieve the desired result. On the one hand, it is advisable to represent the process of processing and passing transit trains as a discrete event, since it can be divided into separate technological elements (operations), each of which has its own beginning and end. And the completion of one operation is the beginning of another operation (taking into account interoperation downtime).

On the other hand, the entire transit system is a multiphase train processing process involving many infrastructural and technological subsystems of railroads: tracks, separation points, locomotive and car depots, parks of technical stations, etc. So globally, the entire technological process in railroad transport represents the interaction of a set of subsystems, elements that, speaking in the language of agent modeling, represent a set of agent populations. Therefore, the second important approach in the development of a simulation model will be agent-based modeling.

Taking into account the above, two approaches will be used in the development of a simulation model of the operational process of the transit line in the railroad direction: discrete-event and agent-based modeling.

The process of following a train along a route and its maintenance at transit technical stations can be represented as a process of servicing a demand in a set of serial and parallel mass service systems. Most of such systems, taking into account the peculiarity of rail transport, are MSSs with a limited number of places in the queue and with waiting. For example, an interstation crossing has a finite capacity (the number of blocks of sections) and provides for the possibility of stopping a train while waiting for the enabling signal of a passing traffic light. Then the total time of stay in such a MSS can be represented as:

$$\begin{aligned} T_{general} = & \left\{ \left(\sum_{i=1}^{N_1} t_{operation.i} + \sum_{i=1}^{N_1} T_{pending\ operation.i} \right)_{technical} \right\}_{k_1} + \\ & + \left\{ \left(\sum_{i=1}^{N_2} t_{operation\ i} + \sum_{i=1}^{N_2} t_{pending\ operation\ i} \right)_{intermediate} \right\}_{k_2} + \\ & + \left\{ \left(\sum_{i=1}^{N_3} t_{movement.i} + \sum_{i=1}^{N_3} t_{pending\ operation.i} \right)_{driving} \right\}_{k_3}, \end{aligned} \tag{1}$$

where N_1, N_2, N_3 is the total (possible) number of technological operations at technical stations, intermediate stations, and the average number of block sections on the tracks of the selected railroad direction, respectively; k_1, k_2, k_3 – total number of technical stations, intermediate stations, and interstation sections on the selected railroad direction; $t_{operation.i}$ – normative duration of the i-th technological operation; $t_{pending\ operation.i}$ – possible waiting time for the i-th technological operation; $\left(\sum_{i=1}^{N_1} t_{operation.i} + \sum_{i=1}^{N_1} t_{pending\ operation.i} \right)_{technical}$ – transit train service time at the technical station; $\left(\sum_{i=1}^{N_2} t_{operation\ i} + \sum_{i=1}^{N_2} t_{pending\ operation\ i} \right)_{intermediate}$ – service time (passage) of a transit train at an intermediate station; $\left(\sum_{i=1}^{N_3} t_{movement.i} + \sum_{i=1}^{N_3} t_{pending\ operation.i} \right)_{driving}$ – time of passage of a transit train along the route.

In expression (1), half of the elements ($t_{operation.i}$) are part of the normative technological process, which is standardized in accordance with existing regulations, instructions, and procedures [1, 10]. The other part of the elements ($t_{pending\ operation.i}$)

has a purely probabilistic nature of occurrence and duration, so it is not normalized. In most cases, it is not taken into account, although, according to various estimates, it makes up a larger share of all train service time in railroad transport systems [10]. Then the probability of a technological failure, in accordance with, is the probability of exceeding the actual time of finding the requirement in MSS (finding a transit train in ZTS) of the planned (normative) time:

$$p\left(T_{actual} > T_{normative}\right), \tag{2}$$

where T_{actual} is the actual time of the transit train following the railroad direction; $T_{normative}$ – normative (scheduled) time of transit train following the railroad direction.

From the point of view of the efficiency of logistics processes, premature arrival of goods as well as late delivery is considered a negative phenomenon, and the actual delivery time can be both shorter and longer than the normative one [10]. Therefore, expression (2) should be formulated in the following form:

$$p\left(\left|T_{actual} - T_{normative}\right| > \Delta T_{permissible}\right),$$

or

$$\begin{cases} p\left(\left(T_{actual} - T_{normative}\right) > \Delta T_{arriving\ late}\right), \\ p\left(\left(T_{normative} - T_{actual}\right) > \Delta T_{premature\ arrival}\right)', \end{cases} \tag{3}$$

where $\Delta T_{permissible}$ is the permissible schedule deviation in the movement of the train along the entire tracking route within the railroad direction with the variation $\Delta T_{arriving\ late}$ – for lateness and $\Delta T_{premature\ arrival}$ premature arrival of trains. This limit is set by the relevant infrastructure operators and can vary in a fairly wide range of values, depending on production needs and legal consequences when the participants of the transportation process access the railroad infrastructure for public use [4, 10].

When minimizing the $T_{general}$ value of expression (1), the component of possible expectations of technological operations decreases and the probability of technological failure decreases (2). In this case, it is advisable to choose the general delivery time $T_{general}$ as the main optimization criterion, and to choose the probability of a possible deviation (3) as an additional optimization criterion. In addition, it should be taken into account that the main production resources in the transportation work of railroads are the fleet of locomotives, railroad freight cars, and the carrying capacity of railroads. Then the objective function of the optimization mathematical model will take the following form:

$$\begin{aligned} T_{general} = {} & \left\{\left(\sum_{i=1}^{N_1} t_{operation.i} + \sum_{i=1}^{N_1} t_{pending\ operation.i}\right)_{technical}\right\}_{k_1} + \\ & + \left\{\left(\sum_{i=1}^{N_2} t_{operation\ i} + \sum_{i=1}^{N_2} t_{pending\ operation\ i}\right)_{intermediate}\right\}_{k_2} \\ & + \left\{\left(\sum_{i=1}^{N_3} t_{movement.i} + \sum_{i=1}^{N_3} t_{pending\ operation.i}\right)_{driving}\right\}_{k_3} = \\ & = T_{actual} \to \text{minimum}, \end{aligned} \tag{4}$$

under constraints:

$$\begin{cases} p\left(\left(T_{actual} - T_{normal}\right) > \Delta T_{arriving\ late}\right) < p_{\xi_{being\ late'}}, \\ p\left(\left(T_{normal} - T_{actual}\right) > \Delta T_{early\ arrival}\right) < p_{\xi_{early\ arrival'}}, \\ \left\{m_{locomotive}\right\} \to \min, m_{locomotive} = 1,2,\ldots M_{locomotive'}, \\ \left\{m_{car}\right\} \to \min, m_{car} = 1,2,\ldots M_{car'}, \\ \left\{n_{bandwidth\ is\ actual}\right\} \to \min, \\ n_{bandwidth\ is\ actual} = 1,2,\ldots N_{bandwidth}, \\ \left\{N_{cargo}\right\} \to \min, \end{cases} \tag{5}$$

$p\xi_{being\ late}$, $p\xi_{premature\ arrival}$ – marginal probability of technological failure for railroad transport systems in the case of late and early arrival of trains, respectively; $\{m_{locomotive}\}$ – working fleet of locomotives, units; $\{m_{car}\}$ – working fleet of cars, units; $\{m_{bandwidth\ is\ actual}\}$ – the actual amount of used bandwidth of the railroad direction, pairs of trains; $\{N_{cargo}\}$ – number of transported goods, tons.

Given the complexity and complexity of the undertaking, one of the few means of conducting this type of research is to perform experimental measurements of the simulation results.

The technological process of the transit line of train processing in railroad transport can be expressed as a set of consecutive discrete events. Each train (requirement), arriving at a railroad station, undergoes a corresponding technological operation, thereby being in a separate, discrete element of the technological system. The transition between processing elements is a conditional boundary and does not have its own duration. The simulation follows the processing of the train, showing the gradual transition of the program through the functional modules of one of the free channels of the mass service system. Each module programmatically delays the application for a period of time that corresponds to the specified or estimated duration of the corresponding technical operation. Conditional boundaries for transitions between technical operations will correspond to the moments of transition of the program from one module to another.

This principle makes it possible to programmatically register the moment of entry of the requirement (train, warehouse) into the program module, which will correspond to the beginning of the execution of the corresponding technological operation, and the moment of the exit of the program from the module, which will correspond to the completion of the corresponding technological operation. Thus, the essence of computer simulation of any technological process is to record the moments of transitions of information requirements between certain software modules of the model, which will make it possible to further process data, determine failure probabilities and trouble-free operation of ZTS. The duration of finding requirements in discrete modules of the model is defined as the difference between the time of exit and the time of entry of the information requirement into the module:

$$\Delta t_z = t_{out,process.z} - t_{in,processt.z}, \text{ if } z = 1,2\ldots m, \tag{6}$$

where $t_{out,\ process\ z}$ is the moment of exit of the requirement from module z; $t_{in,\ process\ z}$ – the moment of entry of the requirement into module z. This moment of time coincides with the moment of entry of the requirement into the next module of the model.

The entire process of processing trains on the tracks of transit yards can be represented as the interaction of three consecutive mass service systems:

– the first MSS (QS-1): interstation section – receiving-departure track. This MSS is single-channel since trains from one direction can only be received sequentially. If several arrival stations are contiguous (for nodal stations), a set of parallel, single-channel MSSs will take place;

– the second MSS (QS-2): the receiving and correctional park is the largest and main MSS of the transport and technological line. It is a multi-channel MSS (the number of channels is equal to the number of receiving and sending tracks) with a set of service devices (the number of service devices will be equal to the number of viewer groups);

– the third MSS (QS-3): receiving-departing track – interstation section. This MSS is essentially similar to the first MSS (Fig. 1).

In turn, a two-track railroad direction with automatic blocking can be represented as a sequence of technological subsystems, each of which represents a conditional technological section (Fig. 2).

Fig. 2 (QS-RS) is a module section at an interstation section. It should be noted that when organizing the passage of intermediate (linear) transit trains, according to their technological content, when passing transit trains, it can also be considered as a section of the track.

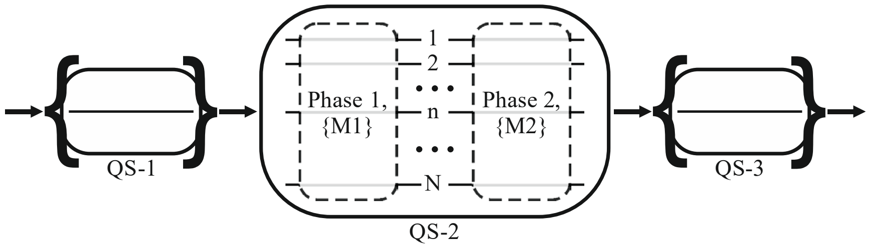

Fig. 1. A set of sequential mass service systems in the transport-technological line of processing transit trains at technical stations

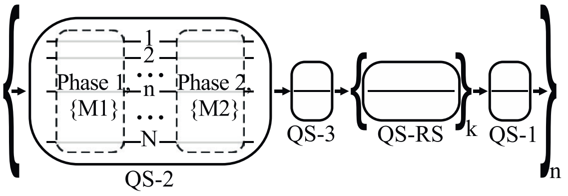

Fig. 2. Structure of the subsystem in the transport-technological line for the maintenance and passage of transit trains for a separate direction of traffic (even/odd) along railroad direction

Thus, the process of promotion and maintenance of transit trains in one direction (even or odd) can be considered as a sequence of railroad sections (technological subsystems) indicated in Fig. 3. At the same time, to simulate the processes of the entire railroad direction, it is necessary to combine the processes of two directions (even and odd) and revolutions of train locomotives. Therefore, the general process of functioning of railroad routes can be represented in the form shown in Fig. 3.

Taking into account the above, the goal of our research is to determine the probability of refusal and the factors affecting it when applications are received in MSS-2 and applications are received in MSS-3. Here MSS-2 is the probability of refusing to accept on time, and MSS-3 is the probability of refusing to send trains on time.

The structure of the simulation model will represent the simulation of two opposing processes of tracking freight transit trains along one railroad direction, in accordance with the structural diagram in Fig. 4.

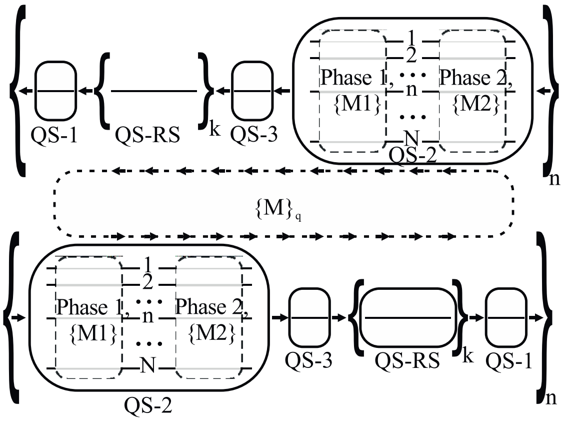

Fig. 3. Structure of the subsystem in the transport-technological line for the maintenance and passage of transit trains along the entire railroad direction. $\{M\}_q$ is a fleet of train locomotives for the maintenance of train traffic in this structural subsystem

Considering that the entire technological process is a sequential set of technological elements, it is logical to use the discrete-event principle of simulation models. At the same time, the simulation of an entire railroad direction involves the simulation of the interaction of many different elements and a set of elements: locomotives, cars, track development, interstation sections, separation points, traffic control systems, etc.

Therefore, the second principle that will be used in the development of the simulation model is the agent principle.

The model includes the following agents:

a) agent Main (class Main) is a basic agent. It is designed for coordination of parameters and processes of the model and interaction of other agents among themselves;

b) the population of RailroadSection agents (class RailroadSection) – main technological elements of the model. Agents simulating the functioning of railroad stations of the rotation of train locomotives. The number of agents of the population will correspond to the number of stations of rotation of locomotives on the railroad direction;

c) population of agents RailroadBlocksEven and RailroadBlocksOdd (class RailroadBlocksEven, class RailroadBlocksEven);

d) population of Train agents (class Entity) – modification of agents of the "requirement" type. It simulates a discrete-event transition between technological operations at infrastructure facilities of transit train depots;

e) population of Locom agents (class Entity) – modification of "requirement" type agents. It simulates the discrete-event transition of technological processes with train locomotives at railroad infrastructure facilities.

Thus, in most cases, the RailroadSection agents and the RailroadBlocksEven and RailroadBlocksOdd agent populations will mostly be responsible for the technological process in terms of infrastructure use. Technological processes in terms of the use of production resources – populations of Train and Locom agents.

Configuring the Main agent. The Main agent of the Main class is designed to coordinate the parameters and all processes of the model and the interaction of other agents among themselves. The simulation of the technological process of servicing transit freight trains on the railroad route begins with this agent.

This agent includes two generators of random phenomena that simulate the arrival of freight trains of even and even directions to the transport and technological system. Each of these generators includes a set of discrete events: generator of random requirements – accumulation buffer – entry into the transport system of the corresponding direction.

In the accumulation buffer, requests are waiting in a queue. When a request is received in the queue, the condition for the availability of the first technical station of the first railroad section is checked. If the entrance to the station is free, the request (train) is transferred to the section, otherwise the request (train) is waiting for a free place at the railroad technical station (Fig. 4).

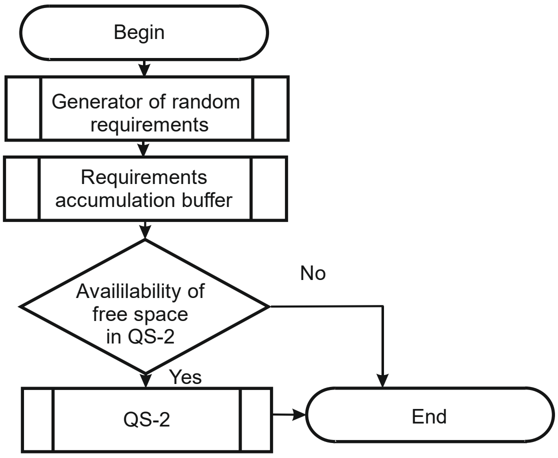

Fig. 4. Algorithm of discrete events in the Main agent

Setting the RailroadSection and RailroadBlocksEven and RailroadBlocksOdd agent populations. The population of RailroadSection agents of the RailroadSection class simulates the operation of railroad sections of the rotation of train locomotives and is a key subsystem of the simulation model. In fact, each of the agents of this population schematically corresponds to a set of mass service systems shown in Fig. 3. It is in these agents that the discrete-event transition of requirements between modules of technological processes is simulated in the service of end-to-end freight trains:

a) arrival of the train to the tracks at the receiving-departing park;

b) maintenance of train composition by crews of observers;

c) replacement of a train locomotive, testing of autobrakes, operations for dispatching a train;

d) sending the train to the first module section of the interstation run.

Since the production resources in this process are surveyor teams and train locomotives, the coordination of the free resource with the train ready for service is ensured. The algorithm of this process is shown in Fig. 5.

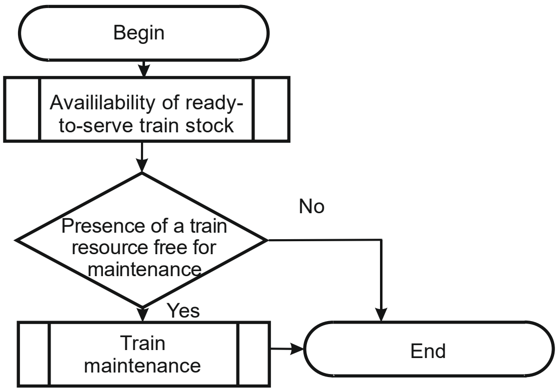

Fig. 5. Algorithm for the use of production resources in the railroad transport system of the RailroadSection agent (a team of surveyors, receiving-departure tracks, train locomotives, the first module section of the interstation section)

It should be noted that all the main production resources of the railroads – the number of inspection crews, the capacity of track development, the locomotive fleet, the number of module yards, etc. are represented in the model by the corresponding parameters that are set in the modeling process and can be optimized.

5. 2. Results of implementing the optimization model of the operational process of the transit line

The simulation model is implemented in the AnyLogic University Researcher (USA) environment using the Java SE compiler (Oracle).

For modeling, typical parameters of the railroad transport-technological line were chosen for the passage of transit freight trains [10], Tables 1, 2.

During the experiments with the simulation model, in addition to the previously specified actual delivery time, additional criteria of the efficiency of the railroad transport system were used:

a) the probability of complete technological failure:

$$\xi_{complete} = \frac{N_{service}}{\sum N}, \tag{7}$$

where $N_{service}$ is the number of trains that underwent service in the system, that is, were passed by the railroad direction, during the model time of the experiment; $\sum N$ – total number of trains that arrived before entering the system;

b) probability of partial technological failure:

$$\xi_{technical} = \frac{N_{late\ service}}{\sum N}, \tag{8}$$

where $N_{late\ service}$ is the number of trains that have been serviced in the system with a delay longer than the set time. That is, trains that in the process of passing through the network due to scholasticism and incoherence of processes had an unproductive idling more than a normative one. In the experiments, the unproductive idling was taken as $t_{unproduktive}$=4 min.

The simulation results are shown in Fig. 6–11.

However, even with a sufficiently large fleet of train locomotives (180 at each of the turning stations), queues of «flour trains» occur quite often, i.e., a situation of partial failure of the system (Fig. 7).

Table 1

Simulation initial parameters

No. of entry	Parameter ID	Measurement unit	Number of measurement units	Optimization possibility
1	Planned volumes of train traffic	pairs of trains per day	85	YES
2	The number of cars in the train	car	50	YES
3	The number of stations on the railway route	unit	5	YES
4	The number of block plots in each district	unit	30	YES
5	The number of tracks for receiving and sending transit freight trains at technical stations	track	9	YES
6	The number of surveyor teams at technical stations for the maintenance of transit freight trains	crew	2	YES
7	A fleet of train locomotives at each station	locomotive	based on norms	YES
8	The minimum regulated time of lateness of freight trains	min.	4	YES
9	Technical speed of trains	km/h	45	YES

Table 2

Characteristics of the execution time of the main technological operations with transit trains and train locomotives at stations

No. of entry	Parameter ID	Density distribution of indicator
1	The stay time of the block plot, min.	triangular (2, 2.5, 5.5)
2	Stay time of the inlet/outlet nozzle, min	triangular (4, 5, 7)
3	Time of inspection of train composition, min	normal ($M(x)=24.3$, $v(x)=0.2$)
4	Time of service of the train locomotive at the point of turnover, h	triangular (0.95, 1, 1.5)

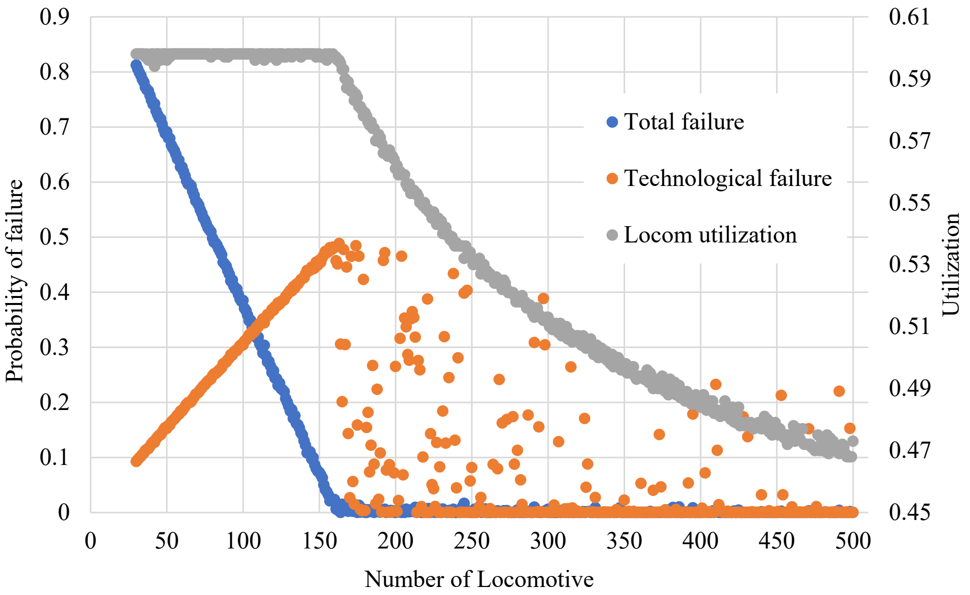

Fig. 6. Dependence of the probability of complete and technological failures on the existing fleet of train locomotives

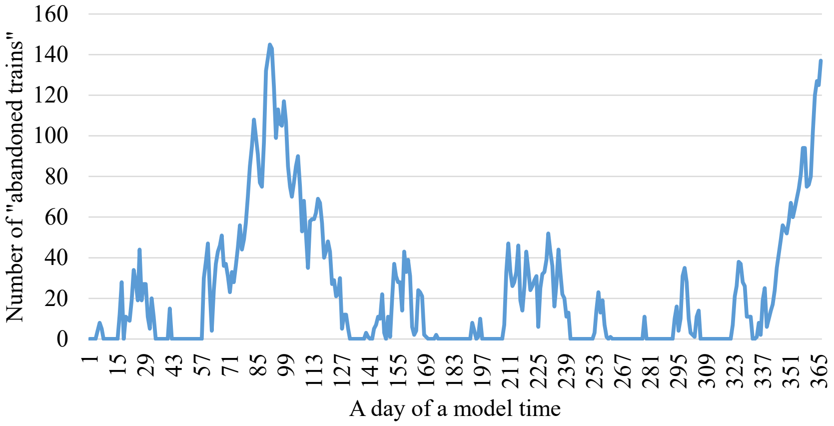

Fig. 7. Queue of «abandoned trains» along the direction (fleet of train locomotives: 180 units)

In general, with a relatively unlimited fleet of train locomotives (300 units at each section and more), the time of passage of a transit train in a railroad direction is subject to a symmetrical distribution law, the best being the normal (71.4 %) and Gamma distribution (86.5 %).

The final results of the optimization of the fleet of train locomotives according to the objective function (4) and the initial data (Table 1) are given in Table 3.

The distribution density of waiting time and execution of basic technological operations is shown in Fig. 9, 10. Fig. 10 shows the distribution of waiting time for train locomotives before departure from the station. In total, according to experimental data, such a phenomenon was observed for 90 % of all sent trains.

In turn, only 10 % of train sets expected a train locomotive before departure (Fig. 11), which indicates a significant imbalance between the volume of traffic and the available fleet of locomotives.

However, as noted above (Fig. 6), only such a ratio of locomotives to the size of train traffic can ensure a sufficient level of technological reliability in railroad transport systems.

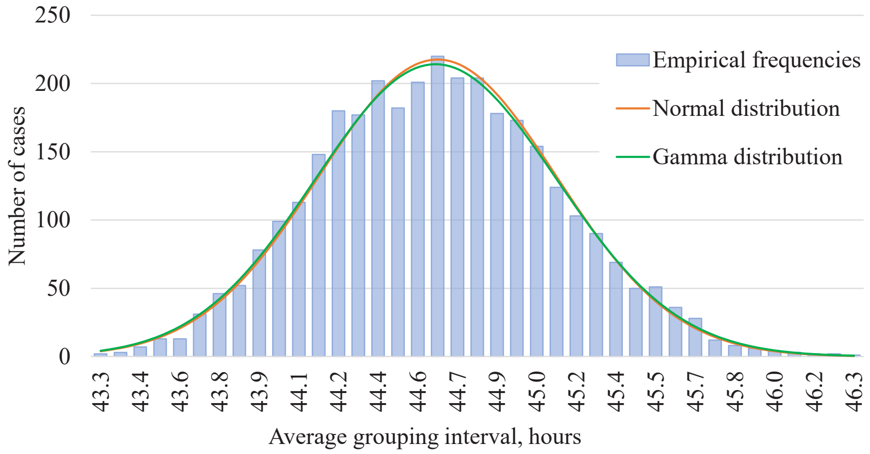

Fig. 8. Density of the distribution of transit train tracking time along the railroad direction (the fleet of train locomotives is 300 units at the norm of 180)

Table 3

Simulation results

No. of entry	Parameter ID	Parameter value
1	Calculated fleet of locomotives for each section of rotation	160
2	The average utilization ratio of locomotives	0.58
3	Standard deviation of the estimated transit train tracking time, hours	0.48
4	Average estimated transit train tracking time, hours	44.6
5	Probability of complete rejection	<0.005
6	Probability of technological failure	<0.5

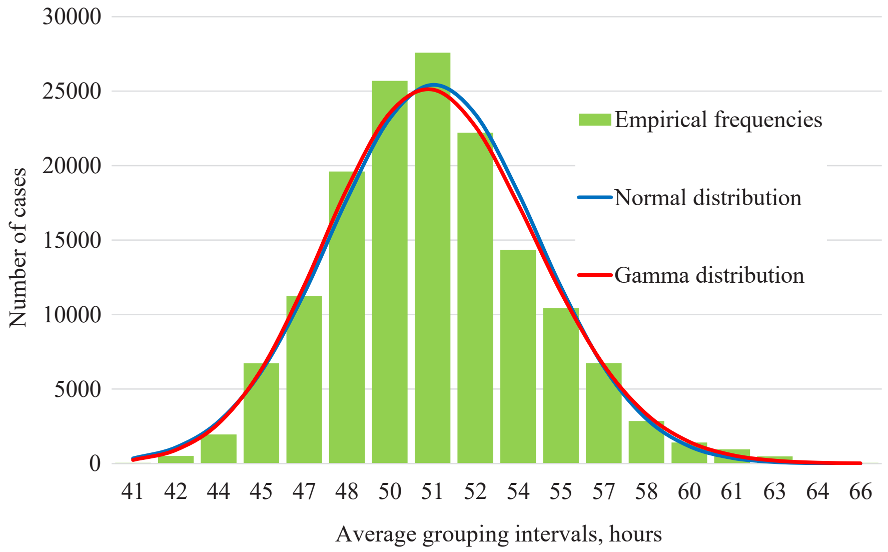

Fig. 9. Density of the distribution of the turnover time of a train locomotive

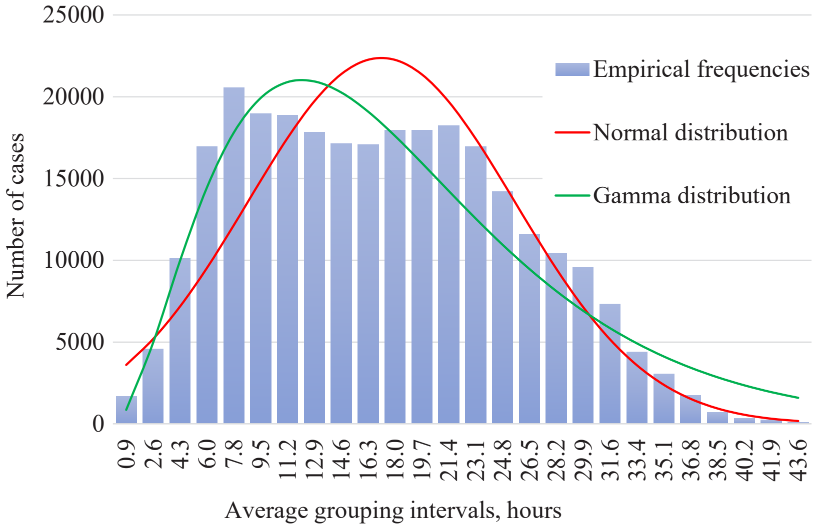

Fig. 10. Density of the distribution of waiting time by the locomotive of a train before departure from the station

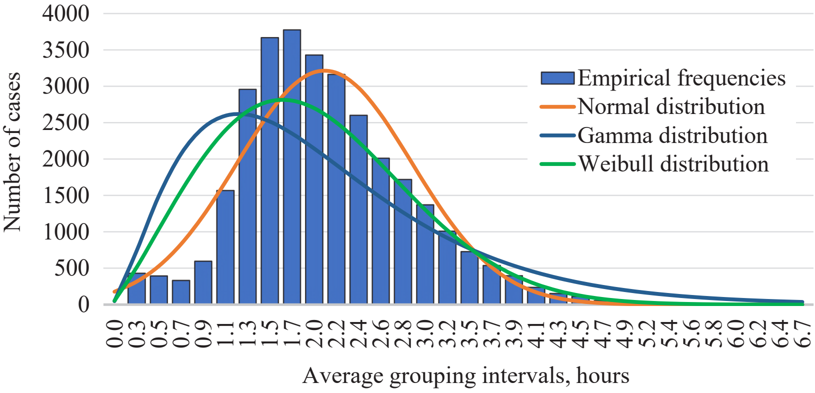

Fig. 11. Density of the distribution of the waiting time by a train set of the train locomotive before departure from the station

6. Discussion of results related to increasing the efficiency of railroad transport infrastructure management on the basis of limit levels of fault tolerance

Owing to the agent and discrete-event approaches, a simulation model of a complex, multi-factor, and multi-element technological process for the organization of end-to-end freight trains on the railroad route has been built. The model simulates the interaction of several important processes at once. In several sections, the rotation of fleets of train locomotives, freight cars as part of through trains, the operation of a module of sections on interstation sections and the operation of technical stations are simultaneously simulated. In contrast to studies [4, 10], our model simulates the interaction of several, or rather five, sections of rotation of train locomotives at once (Fig. 2). Such a large-scale approach in the simulation was implemented owing to the capabilities of object-oriented programming of Java technology (Oracle) and made it possible to optimize the entire process immediately according to the criterion of the minimum delivery time in accordance with the objective function (4) and constraints (5).

The first series of experiments demonstrated an extremely unstable process of functioning of the railroad direction, whereby the standard size of the locomotive fleet (55 units) leads to a complete stop of the system (Fig. 6). In the segment from 30 to 160 locomotives, the probability of a complete stoppage of the system and the technological system is quite high (Fig. 7). At the same time, the utilization factor of the locomotive fleet fluctuates within the optimal range (0.55–0.65), which indicates the sufficiency of traction resources in the railroad system if the reasons are analyzed by classical approaches.

Unstable functioning of the railroad direction in this range of changes in the locomotive fleet arises not only from the lack of locomotives but also from the internal "natural" processes of inadequate inter-coordination of all subsystems of railroad transport.

A significant imbalance in the number of train locomotives is also confirmed by the fact that in the structure of locomotive turnover time, 30 % of the time is spent waiting for the locomotive to leave the train from the station (Fig. 10). The modeling of stochastic processes makes it possible to detect the occurrence of failures associated with waiting for free channels or service devices and waiting for service requests by devices or service channels (Fig. 10, 11). However, with an excess number of train locomotives, the tracking time of a through train along the railroad direction has a normal distribution (Fig. 8). However, even with a significantly increased fleet of train locomotives, the transportation process will not be stable: the probability of technological failure will be 0.3–0.5 (Table 3).

The main result of our research is that the fleet of train locomotives is a priority element in ensuring the required level of fault tolerance of technological processes of railroad transport systems.

In addition, the existing standards, methodologies, and instructions do not make it possible to completely automate the transportation process, which is impossible without "manual" management under an operational mode, mainly when managing the locomotive fleet and "abandoned trains" (Fig. 6, 7).

In the developed simulation models, it was not possible to fully take into account the "manual" element, namely dispatcher control of reserve locomotives. Due to stochastic processes, there are periodically situations with an imbalance of transportation work on odd and even directions (Fig. 3, 7), which requires manual adjustment by reserve locomotives. In addition, the study takes into account work only with through trains while other types of trains are not taken into account (Fig. 2, 3).

A further priority area of research is the determination of the parameters of the railroad transport system, in which it will be possible to implement the transportation process under an automated mode.

7. Conclusions

1. A simulation model of the interaction of five sections of the rotation of train locomotives has been built. A feature

of the model is the use of an object-oriented approach of Java (Oracle) technology, which made it possible to combine in one simulation the process of rotation of locomotives, cars, and the operation of fleets of technical stations and module sections of interstation sections.

2. It has been proven that with the existing regulations and scientific and applied approaches to planning the operational work of railroads, it is impossible to solve the issue of "abandoned trains" and automate the transportation process.

The problem of "abandoned trains" has a solution but, to this end, it is necessary to increase the fleet of train locomotives by 150–200 % relative to the existing standards. At the same time, even with an unlimited fleet of train locomotives, there is a fairly high probability (up to 30–50 %) of technological failures, that is, unproductive delays in the movement of transit trains along the network, which is explained by the "natural" features of rail transport.

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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