

Проведено дослідження ефективності організації передавальних поїздів в розвинених залізничних вузлах за критерієм сукупних вагоно-годин простою під накопиченням. Розроблені дискретно-подієві імітаційні моделі (Java SE, AnyLogic) організації передавальних поїздів за «жорстким графіком» та за накопиченням до норми составів. В моделях враховано стохастичну природу надходження вагонів у пункти накопичення та дотримання составів до встановленої норми. При моделюванні вважається, що колійний розвиток залізничних станцій та внутрішньовузлових ходів є раціональним, та несуттєво впливає на затримку руху передавальних поїздів. Графік руху передавальних поїздів є раціональним та ритмічним. Пропускна спроможність перегонів вузла та переробна спроможність підсистем залізничних станцій є достатніми.

Експериментально проведено порівняння ефективності чотирьох моделей організації передавальних поїздів, у тому числі «гнучкою моделлю», яка поєднує відправлення за накопиченням до норми состава і «жорстким графіком» одночасно. Встановлено, що мінімальні вагоно-години накопичення досягаються при організації передавальних поїздів комбінованим варіантом: одночасне відправлення і за «жорстким графіком» і накопиченням до норми. Результат експерименту виявив найбільш ефективний варіант організації передавальних поїздів, а саме комбінований варіант. Даний варіант передбачає, що при наявності достатньої кількості вагонів у пункті накопичення поїзд відправляється раніше (відправлення за накопиченням до норми), інакше – через розрахунковий середній інтервал (варіант відправлення за «жорстким графіком»). Організація передавальних поїздів за «жорстким графіком» потребує організації додаткових поїздів, інакше суттєво зростає черга із вагонів у пунктах накопичення. При збільшенні добової кількості поїздів на 10–11 % процес формування та відправлення стає достатньо надійним та ефективним.

Зазначені рекомендації дозволять удосконалити типовий процес роботи залізничних вузлів у частині диспетчерського контролю за формуванням, відправленням та пропуском передавальних поїздів у внутрішньовузловому сполученні

Ключові слова: розвинений залізничний вузол, час доставки, графік руху поїздів, імітаційне моделювання, стохастичний потік

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IMPROVEMENT OF EFFICIENCY IN THE ORGANIZATION OF TRANSFER TRAINS AT DEVELOPED RAILWAY NODES BY IMPLEMENTING A "FLEXIBLE MODEL"

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1. Introduction

In a scientific environment, specialists in transport technologies and organization of transportation by railroads have been constantly discussing the way to organize trains

along railroad tracks, railroad stations and nodes. Two basic variants are being considered: dispatching trains upon accumulation to the standard of a train and dispatching trains in line with a "rigid schedule", regardless of the available number of wagons.

It is believed that the accumulation to the standard (especially under low intensity of wagon arrivals to accumulation points) increases the wagon-hours of accumulation. This process, in turn, leads to a significant increase in the duration of train formation, and as a result, to an increase in the technological terms of cargo delivery.

Organizing in line with a “rigid schedule” ensures proper regularity in the interaction “railroad – customer”, however, this technique is believed to fail to provide for the proper efficiency of utilizing traction rolling stock and railroad transport infrastructure because of a typically incomplete composition of trains.

It is difficult to explore the specified issues using analytical models because of the complexity and scale of the process, especially when taking into consideration the probabilistic arrival of wagons to accumulation points. Therefore, resolving the specified scientific and applied task remains relevant; it can be solved at present by applying imitational simulation.

2. Literature review and problem statement

An analysis of current research in the field of improvement of technology of work at developed railroad nodes reveals that special attention is being paid to the optimization of process of disbandment-forming trains at technical stations and the formalization of models of operation of transport systems. Construction of a mathematical model of optimization of sorting process is described in paper [1], based on the allocation of forming tracks at a sorting station for outgoing freight trains taking into consideration realistic constraints for the schedule of trains, timely arrival and departure, as well as the throughput capacity of the track. It should be noted that this model makes it possible to temporarily keep freight wagons at a combined track specially intended for this purpose, but it does not include different variants for trains dispatch.

Paper [2] noted the impact of basic technological parameters on the probability of failure and the duration of failure-free operation of timely receipt and dispatch of freight trains. Such an approach takes into consideration the technological features of wagon flows, but it is imperfect because it does not solve a given task comprehensively for the railroad network. In research [3], authors pointed to the aspect, similar to earlier studies, on operability and fault-tolerance of technological processes at railroads, but only in terms of transporting dangerous cargoes.

It is noted in paper [4] that modeling of technological processes at railroads should involve discrete-event simulation, because this technique makes it possible to build models that could, with high adequacy, formalize technological processes at fleets of railroad stations. One of the major benefits of such a simulation is the possibility to study a complex stochastic process and to determine delays between the stages of train processing at the tracks of parks. However, these models cannot be used to assess the effectiveness of functioning of marshalling parks where wagons are accumulated to the standard of a train. Adjusting the process of forming grouped trains to scheduled traffic, by using appropriate optimization models, makes it possible to accelerate the delivery of cargoes by railroad transport [5]; however, there is the unresolved issue on matching the dispatch of transfer trains at developed rail nodes with heavy passenger traffic.

To analyze and predict the time of delays, to organize trains at section, work [6] reports a model of fuzzy control that provides for the capability to automate the processes of operation of fleets of technical systems taking into consideration the fuzzy parameters of control systems. However, it is unknown if the model could be used to assess the technological processes of marshalling stations at developed railroad nodes. Paper [7] applied the theoretical-methodological toolset from game theories to propose an approach to the formation of optimal mechanism for ensuring the coordinated control over the process of delivery of goods at general transportation nodes. However, the applied methodological toolset of game theories ignores the technological parameters of wagon flows and the characteristics of the cargo delivery process.

Study [8] addressed the acceleration of forming grouped trains by employing algorithms and reducing operating costs associated with the stay of rolling stock at marshalling stations. Thus, one can argue that the criterion for evaluating the appropriateness of assigning the destinations for freight trains, used by the authors, is the criterion of minimizing wagon-hours spent on the accumulation and processing of wagons. However, there is no assessment of the impact exerted on the specified indicators by the technique used to organize trains.

Study [9] outlined patterns in the process of accumulation of wagons in line with a “rigid schedule” (departure of trains on a daily basis at the same time and their motion in line with the interconnected schedule points along the entire length of the route). This confirms the prospects for application of mathematical models on rational organization of transfer trains at developed railroad nodes. The authors consider the process of wagons accumulation in detail, taking into account the arrival of individual groups of wagons that determine the cost of wagon-hours on the accumulation of wagons. Paper [10] notes that the downtime of wagons due to the accumulation of trains is an important part of the basic qualitative indicator of marshalling station performance – the total idling time of wagons at a station. In addition, the daily average costs of wagon-hours for accumulation for each railroad destination is an important parameter in the calculation of train plan formation.

Article [11] analyzed the impact of systemic differences in railroad transport between North America and Europe, and provided a brief overview of relevant optimization models. Compared with North America, railroad companies in Europe faced serious economic problems in handling freight flows. The results confirmed that the North American rail companies spend less for transportation than those in Europe, due to the fact that the North American models are mainly focused on searching for short distances for each car, while the European ones – on the high level of accumulation to the standard of a train. It should be noted that the study does not take into consideration the features of technological processes at developed railroad nodes.

Optimization of the process of formation (disbanding) of trains at technical stations using a mathematical model with fuzzy costs for the planning of train formation is reported in paper [12]. The described model considers costs in three variants: optimistic, normal, and pessimistic. The adjustment of parameters employs a three-stage method using the approach for planning experiments. To assess the efficiency and effectiveness of the proposed algorithm, re-

sults are compared with the results from modern software for optimization. The train formation plan defines the route, frequency of trains, requirements to trains; it, however, does not account for the possibility of dispatching trains in line with a “rigid schedule”.

Paper [13] suggested a mathematical model for delivering bulk cargoes along the routes of railroad transport, which takes into consideration the interaction between production, transportation, and consumption. This model makes it possible to solve a wide range of tasks faced by suppliers and consumers when choosing railroad transport, and is associated with the planning and control over operational work of stations. However, the proposed mathematical model of cargo delivery along the routes of rail transport does not make it possible to simulate different variants for the organization of transfer trains at a node, specifically the accumulation to the standard, in line with a “rigid schedule”, and combined. Their practical use would make it possible to more accurately and reasonably standardize the idling of wagons under accumulation.

Study [14] proposed reducing the cost of cargo transportation, as well as decreasing unproductive time delays. The authors identified factors that affect the timing of cargo arrival. Paper [15] suggested a methodology whose application makes it possible to choose a rational technology of delivery of goods for industrial purposes in international traffic. However, the remaining unresolved issues are related to the possibility to simulate the process of cargo delivery for alternative variants, depending on technological parameters.

A research reported in [16] confirms that the process of wagon accumulation depends on the standard for train composition and on the technique for fulfilling the schedule of trains for departure. The authors established three variants of train accumulation:

- a constant standard of a train when dispatching trains in line with a flexible schedule;
- a flexible standard of a train when dispatching trains in line with a flexible schedule;
- the standard of a train is limited by the set range when dispatching trains in line with a “rigid schedule”.

However, it should be noted that the above studies do not take into consideration the stochastic nature of wagon arrivals to accumulation points. There are no comprehensive models to evaluate efficiency for the criterion of minimal (aggregate) wagon-hours of accumulation (under the condition for stochastic arrivals of wagons to accumulation points). According to [17], under the existing system of organization of work at a large node the average length of a local wagon's stay was 62.17 hours, while the largest share (97.8 %) of time accounted for the duration of a wagon's stay at technical stations. Compared with the “peak” in local work in 2007, the idling of a wagon at a single technical station rose from 8.88 to 15.89 hours in 2017 (by 78.9 %). That necessitates conducting additional research by constructing complex simulation models and determining experimentally the total hours of downtime by wagons under accumulation under different techniques for the organization of transfer trains.

3. The aim and objectives of the study

The aim of this study is to identify patterns in the influence of techniques for the organization of transfer trains at developed railroad nodes on the efficiency of transfer traffic

based on the criterion of minimal (aggregate) hours of wagons accumulation at the points of train formation. Results of the experiments would make it possible to establish an optimal model of the organization of transfer trains, which in practice, only through organizational changes, would ensure reduction of wasted time when forming transfer trains and, as a consequence, would contribute to a decrease (on average) in the duration of cargo delivery.

To resolve the specified scientifically-applied task, the following must be done:

- to substantiate criteria of efficiency for the technological system of organization of transfer trains;
- to build simulation models of the organization of transfer traffic in line with a “rigid schedule” and the accumulation of trains to the established standard on the condition of stochastic arrivals of wagons to accumulation points;
- to establish experimentally the most effective model of the system of organization of transfer trains based on the defined criterion.

4. Research toolset and criteria of efficiency of transfer traffic at developed railroad nodes

4.1. Substantiation of the criterion of effectiveness of the technological model of organization of transfer trains

The process of organization of transfer trains at developed railroad nodes can be generally represented as a sequence of three operations:

- 1) accumulation of local wagons at points of transfer trains formation, that is, at marshaling (forward direction) and freight (backward direction) stations;
- 2) formation of a transfer train;
- 3) departure and run of the train in intranodal traffic.

All these procedures are performed in the same order regardless of the technique of organization of transfer trains: in line with a “rigid schedule”, accumulation to the standard, or other ways. In addition, regardless of the variant for organization of transfer trains, the duration of technological operations involving them at each particular station (duration of disbandment, end of forming, processing the trains for departure) and the duration of their motion (traffic along station-to-station distances) in the middle of the node (one route) will be the same.

Thus, the total time of the organization of transfer trains at developed railroad nodes, in terms of its duration, would mostly differ only by the time spent for the accumulation of wagons at forming stations. Thus, the total time on wagons accumulation at forming stations will be applied as a criterion for the evaluation of technological effectiveness of models of organization of transfer trains at developed railroad nodes.

4.2. Theoretical substantiation and construction of a simulation model of the organization of transfer trains at developed railroad nodes

Given the above, simulation of the process of accumulation takes the following schematic form: generator of request submissions – collector (queue) – delay (imitation of the end of train forming, processing for dispatch and run of a train between a forming station and a destination station) (Fig. 1).

A flow of wagons arrival to the point of accumulation can be represented much simpler because it is stationary (continuous), ordinary (conditionally) and has no aftereffect. The number of wagons that arrive per unit time (24 hours) is

governed by a Poisson distribution, time intervals of wagons arrival – exponential.

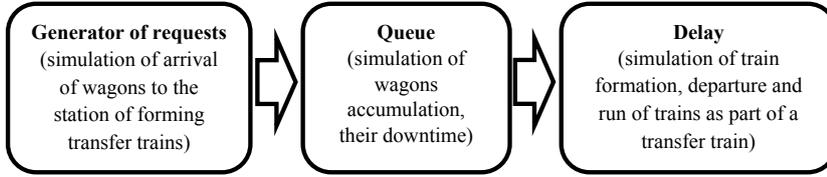


Fig. 1. Structural-logic scheme of simulation of the process of organization of transfer trains at developed railroad nodes

The organization of trains based on accumulation to the standard when a request arrives to the second unit, a check procedure is enabled:

$$m_q \geq m_{norm}, \quad (1)$$

where m_q is the actual number of wagons under accumulation (waiting to be dispatched) at moment t_i of the model time of arrival of the i -th request to unit two of the model, wagons; m_n is the standard of a train (in conditional wagons) along a given railroad direction, wagons.

A train will be dispatched upon the actual accumulation of wagons at the forming station to the standard of a transfer train. In this case, it is believed that the train does not await the nearest schedule point, and is dispatched when ready in line with a dispatcher schedule.

The organization of trains in line with a “rigid schedule” implies that trains are dispatched according to the established schedule of train departures. In this case, the ideal schedule is the one that provides for maximum rhythmicity. An interval between trains departures must be the same or maximally equal. The magnitude for an interval is to be determined through the required volumes of traffic at known general average daily wagon flows and the mean composition of a train (the standard of a train):

$$\overline{I_{tr. aver}} = \frac{\overline{N_d}}{m_{norm}}, \quad (2)$$

where N_d is the average daily number of local wagons.

Each new transfer train will leave a forming station at time point t_{j+1} at any quantity of requests (wagons) in unit two $m_q > 0$, even if there are no enough wagons for the formation of a full transfer train, that is, $m_q < m_{norm}$.

A discrete-event simulation (DES) will be the form of imitation modeling because the process of arrival of wagons to accumulation points, formation, dispatch and motion along the sections by transfer trains can be represented as a discrete-event one. This argument for railroad technological processes was substantiated in detail in papers [2, 4, 5].

Key in the experimental analysis of variants of organization of transfer trains is the measurements between the phase transitions of arrival and sending the requests (wagons) in units 1, 2, and 3 of simulation models (Fig. 1). Considering it, each request must possess a capability to register the time points of phase transition between the states of the technological system – units in the simulation model. One of the most convenient ways to implement the specified function is to apply object-oriented principles. When applying them, every single request in modelling would represent a class instance with additional fields t_{1-2} , t_{2-3} . These fields, accordingly, represent the time points of phase transition of

each individual request between units 1–2 and 2–3. Then the total wagon-hours of downtime during accumulation are:

$$B_2 = \sum (t_{2-3} - t_{1-2}). \quad (3)$$

It is this approach that would ensure a “number-based” accounting of each individual request (wagon) over the entire process of simulation. The specified study technique makes it possible to establish as which time point within a range of model time each separate wagon (request) arrives to the point of accumulation (variable t_{1-2}), and at which time point within the model time this particular wagon moved to another phase of processing (the end of forming, processing for dispatch and departure), (variable t_{2-3}). Among most of available means for studying transportation processes and systems (analytical, graphical-analytical, or imitation (not object-oriented but, for example, functional) simulation), a given technique is practically the only one that makes it possible to explore the downtime between operations (that is, the difference between time points of variables t_{2-3} , t_{1-2}) for stochastic processes on transport over a significant duration of real time (5, 10, or more years).

One of the few (among those available for applied research) tools to design simulation models based on the object-oriented principles is the *Java* compiler and the programming environment *Eclipse*. Therefore, the simulation model was constructed by means of the programming language *Java*, employing additional libraries from *AnyLogic*.

The model has been implemented as the relationship of three generations of requests. The first generation, units: *sourceCars* – a generator of the flow of requests-wagons (class *Cars*) with containers; *queue* – a queue that simulates the process of accumulation of a transfer train at the forming station; *hold* – simulation of ending the formation of a train and dispatching wagons from station as part of the transfer train; *sink* – collecting statistics on the processed requests.

The second generation, units: *sourceTrain* – a generator of requests-trains (class *Train*) in the form of scheduled daily volume of traffic of transfer trains; *queue1* – queue that simulates the availability of free slots in the schedule of transfer trains; *hold1* – simulation of train departure in line with a schedule time slot. This unit lacks a unit of the type *sink*, because the same requests-trains for each new day are included in the schedule of trains.

The third generation, units *sourceTimer* and *sink1* are intended to count modelling time. A request is generated every minute (in line with normal distribution) that corresponds to the flow of time. This unit is used only when simulating a “rigid schedule” of transfer trains departure.

The parameters of the model are *wagonsOnDay* (type int) – a daily wagon flow, *normCarsInTrane* (type int) – the standard of a transfer train, wagons; *onTable* (type boolean) – a switch of simulation conditions in line with a “rigid schedule” or under accumulation.

Additional variables of the model: *trains* (type int) – required volume of train traffic; *wagonsToTrain* (type int) – the actual number of wagons dispatched in a train; *departureInterval* (type double) – the average interval of train departures; *lastTimeArrive* (type double) – the model time of the last actual departure of a train; *wagonsToTrainForStat* (int type) – the actual number of wagons dispatched in a train.

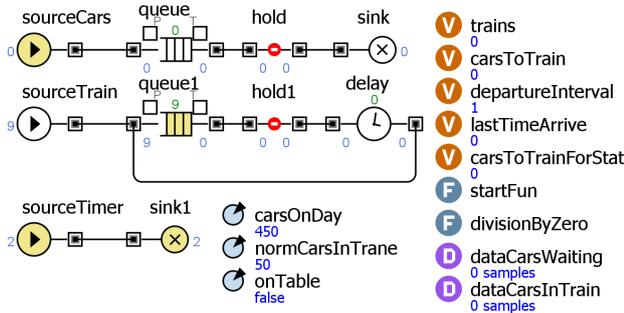


Fig. 2. Simulation model of the organization of transfer traffic at a developed railroad node

When simulating the departure of trains in line with a “rigid schedule”, at the start of the model one implements the Java code of function `startFun()`, which defines: the daily required number of schedule time slots (*trains*), the average interval between train departures (*departureInterval*) and the model time of departure of the first train (*lastTimeArrive*):

```
if (onTable){
    trains = (int)(wagonsOnDay/normCarsInTrane);
    departureInterval = 1440 / (trains);
    lastTimeArrive = departureInterval;
}
```

Each minute, another Java-code is implemented that simulates the departure of a train in line with the next rigid time slot of the schedule:

```
if (onTable && time() >= lastTimeArrive){
    hold1.setUnited(false);
    lastTimeArrive += departureInterval;
}
```

When simulating the departure of trains based on the accumulation to the standard of a train, when each new request-wagon is received, a Java-code is implemented in unit *queue* that checks availability of the required number of wagons (according to the standard) in order to form a complete train:

```
if (!onTable){
    if (queue.size() >= normCarsInTrane){
        wagonsToTrain = normCarsInTrane;
        wagonsToTrainForStat = wagonsToTrain;
        hold.setUnited(false);
        hold1.setUnited(false);
    }
}
entity.time_Q = time();
```

At the input to unit *queue*, parameter *time_Q* for each request-wagon is assigned the actual model time that corresponds to the onset of counting down the downtime of a wagon under accumulation at the forming station. When requests-wagons exit unit *queue* (an imitation of the early completion of the formation of a transfer train), the statistics are collected on the downtime of wagons under accumulation, followed by systematization:

```
dataTrainWaiting.add(time() - entity.time_Q);
```

Procedure *dataTrainWaiting* defines the general probabilistic characteristics of distribution of downtime of wagons under accumulation: mathematical expectation, standard deviation, probability density, etc.

4. 3. Implementation of a simulation model of the organization of transfer trains using Odesa railroad node as an example. Original settings for basic modeling

The model was implemented for transfer traffic at the Odesa railroad node, one of the largest in Ukraine. This transportation hub is characterized by considerable volumes of loading operations that are carried out in the interaction between rail and maritime transport. Specifically, this transport node generates a considerable amount of container transportation between the railroad stations Odesa-Lisky and Odesa-Port.

In the specified process, Odesa-Lisky is the equivalent of a “dry port” – a transport-warehouse complex whose functional purpose is the accumulation of containers that arrive in Odesa region by railroad and road transport. It should be noted that transfer trains towards the station Odesa-Port are formed at this station, bypassing technical stations at Odesa railroad node.

The out-of-class station Odesa-Port is a freight station, intended for immediate servicing of transshipment terminals at the Odesa Sea Commercial Port.

Thus, along the same direction (conditionally direct), transfer trains with containers are formed at the station Odesa-Lisky and travel to the station Odesa-Port. Along the opposite direction (conditionally backward), those containers that arrive by vessels to the ports in Odessa region are transported mostly by transfer trains, formed, among others, at the station Odesa-Port, to the station Odesa-Lisky to be dispatched beyond Odessa transport node.

The original settings of the model correspond to the peak period of intensity with an average daily wagon flow of 450 wagons. The standard transfer train consists of 50 wagons.

4. 4. Constraints and assumptions in modeling. Validating the programming code, checking adequacy of the model, and estimating the reliability of results

In developing the model, it is considered that:

1) the incoming flow of transit trains is the simplest and, therefore, is of the Poisson type;

2) under condition for the organization in line with a “rigid schedule”, the schedule of trains is a rhythmic and rational: the time slots within the schedule of transfer trains are distributed over 24 hours at approximately equal intervals, which is $1,440 / N_{tr}$. (N_{tr} is the average daily number of transfer trains). At the organization of trains under accumulation to the standard, trains depart from the forming upon readiness, in line with the dispatcher schedule;

3) the track development of stations and the technical equipment of railroad node’s passages is rational. The number of locomotives for transfer traffic and other technological elements (receiving-dispatching tracks at station parks, locomotive crews, etc.) is sufficient. The available throughput and processing capacities of railroad transport subsystems of the node are satisfactory and do not significantly affect the delay at accumulation, formation, dispatching and receiving of transfer trains;

4) a request in the subsystems of stations and the node (forming parks, approach sections) is chosen based on the *FIFO* principle (first in – first out): that request is selected that entered the state of waiting earlier.

We have validated the simulation model both when testing its individual units and the model in general. The model fully implements the algorithm of forming the trains upon accumulation and forming when they are dispatched in line with a “rigid schedule”.

The required level of reliability of modelling results is ensured by determining the minimal number of iterations and the minimal duration of the modeling time of each experiment [2]. It was established that reliability at a level not less than 0.95 is provided at four iterations and a modeling time not less than 150 months.

5. Results of experiments involving a simulation model of the organization of transfer traffic of trains at a developed railroad node

Simulation that involved basic source parameters was conducted for four variants of the organization of transfer trains:

1. When dispatching after accumulating to the standard of a train.
2. When dispatching in line with a “rigid schedule”.
3. When dispatching in line with a “rigid schedule”, provided that technological reliability is at the level of 95 %. A given technique of organization implies increasing a daily number of trains in order to reduce the average interval of their departure and, as a consequence, to decrease the probability of a failure to timely dispatch wagons from accumulation points.
4. A flexible model represents a combination of the first and second: if there is a sufficient number of wagons at a point of accumulation, the train is dispatched earlier (a first model); otherwise – after the estimated average interval (a second model).

We obtained the following results from simulation (Table 1, Fig. 3–5).

To determine the size of an increase in the daily number of trains when organizing transfer trains in line with a “rigid schedule”, we performed an additional series of experiments (Fig. 7, Table 1).

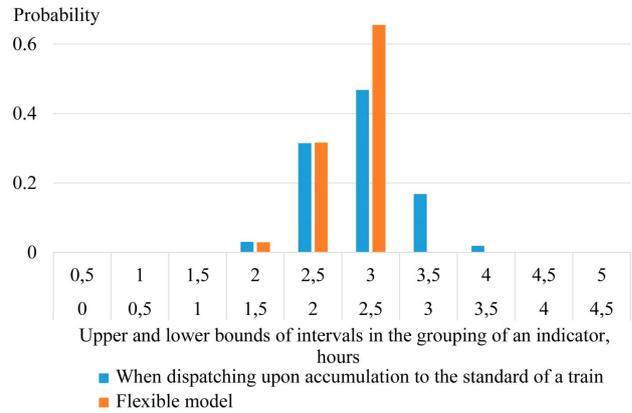


Fig. 3. Distribution density of the probability of intervals in the departure of transfer trains when they are organized at accumulation to the standard of a train

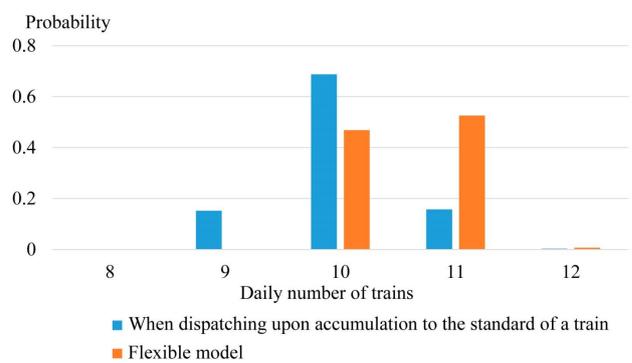


Fig. 4. Distribution density of the probability of the daily number of transfer trains

Each experiment is accompanied by appropriate collection, systematization, and analysis of statistical data, as well as the technological indicators for appropriate models of the organization of transfer trains. Specifically, we determined variance in the volume of a queue of wagons that are at accumulation points.

Table 1

Original settings and results from basic simulation

Original settings and results from basic simulation	Variant and model name			
	1	2	3	4
	When dispatching upon accumulating to the standard of a train	When dispatching in line with a «rigid schedule»	When dispatching in line with a «rigid schedule», provided that technological reliability is at the level of 95 %	Flexible model
Original parameters for simulation:				
Average daily wagon flow, wagons	450	450	450	450
Standard of a train, wagons	50	50	50	50
Planned volume of trains' traffic per day	9	9	9+4	9
Incoming flow of wagons to the points of accumulation	Poisson			
Simulation results:				
Mean value and variance in the number of trains per day	9.0; 6.3 %	9.0; 0 %	13.0; 0 %	9.5; 5.4 %
Mean value and variance in the interval of dispatching trains, hours	2.6; 14.0 %	2.6; 0 %	1.8; 0.0 %	2.5; 8.4 %
Mean value and variance in the number of wagons in a train, wagons	50; 0 %	49.9; 1.2 %	34.3; 16.9 %	47.2; 8.4 %
Mean value and variance in the duration of wagon downtime under accumulation, hours	1.3; 62.2 %	15.1; 63.9 %	0.9; 57.7 %	1.2; 59.7 %
The average queue size during accumulation, wagons	24.4	284.8	17.1	23.2

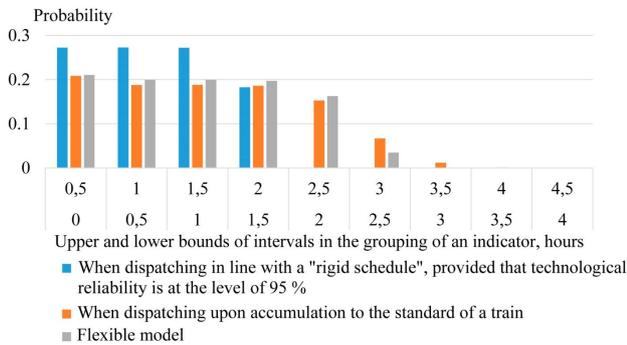


Fig. 5. Distribution density of the probability of downtime of wagons under accumulation

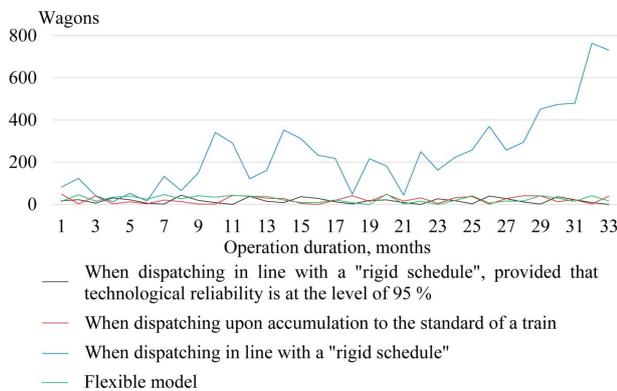


Fig. 6. The formation of queues of wagons that are awaiting departure from accumulation points and the formation of transfer trains

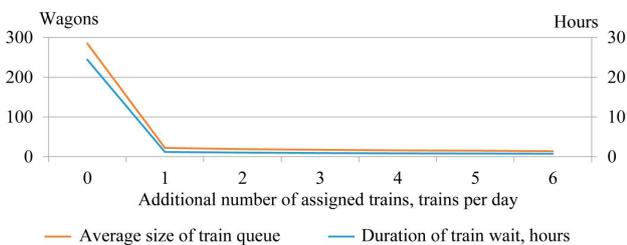


Fig. 7. Dependence of the mean time of downtime and the volume of wagons queue under the accumulation on the number of additional trains (24 hours) when transfer trains are organized in line with a “rigid schedule”

6. Discussion of results from simulation modeling of the organization of transfer trains at a developed railroad node

Modelling was able to cover all the variants of the organization of transfer trains that are currently used, and could potentially be implemented at modern developed transport nodes.

When dispatching transfer trains in line with a “rigid schedule”, we observed a sharp increase in the average downtime of wagons under accumulation (284.8 hours Table 3), indicating a gradual reduction in the fault-tolerance of a railroad technological system. Such a phenomenon can be explained by that when dispatching in line with a “rigid schedule”, there is a high probability of dispatching incomplete trains, which, within each day, at the planned volumes

of traffic (equal to 9 per day, Table 3), does not make it possible to dispatch all wagons. Hence, the accumulation of wagons increases in the “avalanche” manner (Fig. 6). To ensure the proper level of technological reliability, it is necessary to forecast additional (unscheduled) transfer trains, that is, to increase the planned train flows. Thus, it was experimentally determined that while increasing the number of daily trains by one (11 %) and larger each day, the average downtime of wagons under accumulation and the size of the queue of wagons at a point of accumulation reduces to standard indicators (Fig. 7, Table 1).

On the other hand, the volume of traffic of transfer trains in line with a “rigid schedule” should be determined not based on the condition for complete trains, that is, the number of wagons that corresponds to the standard of a train along a given railroad direction. Given that the distribution of the daily number of wagons is governed by the Poisson law, which, as it is known, is close to symmetric, such a value for the estimated number of wagons per train could be the value equal to about half the standard. The simulation results then would match the variant with additional four trains every day (Table 1) (Fig. 7).

It was established experimentally that at constant volumes of a train flow (nine per day) the most rational variant for the organization of transfer trains is a “flexible model” (variant 4, Table 1). Under this variant, the average downtime of wagons under accumulation would be reduced by 0.1 hour, which over a year would amount on average to 16.5 thousand hours. Given the average cost of load weight for a railroad (USD 185 per ton) and the rate of refinancing in Ukraine (18 % per annum), the total cost savings could be approximately USD 37,000 per year.

It should be noted that a given technique of organization implies “dispatching on readiness”, which, under conditions of heavy train traffic at developed nodes, is not always possible (especially in the morning and evening peak hours when there are intensive intercity and local train flows). Therefore, developed railroad nodes with heavy traffic of passenger trains require a separate study.

7. Conclusions

1. For different models of the organization of transfer trains, only the downtime of wagons under accumulation differs. Therefore, the criterion of effectiveness of the specified process is the average downtime of a local wagon under accumulation, or total wagon-hours under accumulation.

2. We have constructed discrete-event simulation models (*Java SE, Eclipse, AnyLogic*) of the organization of transfer trains in line with a “rigid schedule” and under accumulation to the standard of a train with a possibility of their simultaneous combination. The models take into consideration the stochastic nature of wagons arrival to accumulation points and maintaining trains to the established standard. The models implemented the object-oriented principle, which ensures a “number-based” accounting of time points at the phase transition of each individual request (wagon) over the entire process of modeling. The simulation models that we built cover all variants in the organization of transfer trains that are currently used, and could potentially be implemented at modern developed transport nodes.

3. It was established experimentally that the most effective variant of the organization of trains, based on the criterion for

minimal total wagon-hours of downtime under accumulation, is the combined variant. When there is a sufficient number of wagons at a point of accumulation, a train is dispatched earlier (dispatching under accumulation to the standard). Otherwise, in line with the estimated average interval (the variant

of dispatching in line with a “rigid schedule”). When applying a given variant, we obtained the minimal total wagon-hours under accumulation at constant parameters for the technological system: volumes of trains traffic, the required throughput and processing capabilities of subsystems at a railroad node.

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