1. Introduction

One of the important indicators of the railroad system is the reliability and accuracy of transportation, which are directly associated with the stability of functioning [1, 2]. Underlying the operation of the railroad system is a working timetable (WTT), which is an annual plan for the allocation of time required by the necessary number of trains of different categories to travel along the railroad network. Influence of different kinds of random factors leads to delays in the time of train motion, which, under conditions of interdependence of trains in the timetable, creates the process of delay propagation over long distances. A capability to assess the consequences of delay propagation in a train timetable affects the capacity of a railroad system to confront the disruption of accuracy while performing a transportation process. A characteristic feature of the current model of transportation process on the railroad networks of South America, Africa, Eastern Europe, including Ukraine, is the mixed motion of passenger and freight trains based on the non-cyclic train timetable. Given that a given motion rather negatively impacts the utilization of throughput capacity of railroad subsections, it is an important task to study complex processes of successive delay propagation. This would make it possible to properly distribute the magnitudes of time reserve in train timetables or, in the process of development, to alter train scheduling in order to reduce the influence of detected consequences of delay on the overall throughput capacity.

Thus, it appears relevant to solve the task on modelling a delay propagation in non-cyclic train scheduling on the railroads with mixed traffic.
number of delays of trains at the subsection on the place of their occurrence. Study [4] is similar; its authors performed a statistical analysis of the quality of train timetable implementation at an intermediate station, located at the subsection with significant volumes of freight and passenger traffic. However, a given study addressed the analysis of existing actual delays only; this does not make it possible to examine different variants of delay occurrence and detailed dynamics in the formation of cascading delays. This is explained by the lower level of attention, paid over many decades, to keeping train scheduling on time, especially of freight trains, under actual operation of railroads, by the lack of tools for the automated construction of train timetables, as well as poor theoretical basis related to studying the reliability of train scheduling. However, those railroads where the train timetable is a key mechanism for the implementation of a transportation process, have contributed to the theoretical basis underlying the study into delay propagation. Much research has addressed a given task [5–8].

In paper [5], authors constructed a mathematical model of railroad traffic based on the activity graph, which examines the absorption of delays and allows calculations for the networks of large dimensionality. Research [6] addresses the stability and reliability of non-cyclic train scheduling of passenger trains applying the specialized software PETER, using a high-speed railroad line in China as an example. Work [7] reported a tool to predict delays of passenger trains on the railroads of Germany, designed to support decision making by dispatchers. However, studies based on the comprehensive approach to modeling the delays in non-cyclic train scheduling on railroads with mixed traffic are far from being perfect and fail to take into consideration the patterns of a system for interval train traffic control with respect to the motion of freight multi-car and heavy-weight (exceeding 4,500 tons) trains of different categories.

One of the first approaches to estimating delay propagation in train traffic schedule was outlined in paper [8]. The work employs the theory of mass service in order to model delays of trains at the subsection. The authors obtained an analytical approach to estimating the sequence of train delays based on the construction of the system of mass service. However, the results obtained are rather approximate because the assumptions implying the application of Poisson's distribution law to the number of trains arriving at a bottleneck are refuted by many studies [9].

Research paper [10] reports a method for modeling the dynamics of delay propagation of trains in time and space based on the non-stationary Markovian process. The evaluation of train delays for the sequence of events of arrival and departure is proposed to represent as a stochastic process by altering the time of each event according to the delay probability distribution. In addition, it is assumed that delays may have different probability distributions. However, in contrast to other approaches where such a probability of distribution is determined based on historical data on keeping the standard train timetable, a given study proposed taking into consideration the impact of information that arrives in real time on the uncertainty in the evaluation of train delays using the Markovian properties. It was assumed that the delay of a certain event in the future can be properly predicted based on known delays. That is why a train delay in the future depends on the current delay only, rather than on the delay in events that preceded it. This approach is quite interesting; however, the application of distribution laws and operational information on traffic situation, which is missing, makes its implementation impossible on the railroad network of Ukraine.

Many studies are aimed at defining, based on empirical data on the actual time of train traffic at stations and subsections, the laws of distribution of random variables, such as the number and duration of delays. For example, authors of paper [11], using the method of maximum likelihood (MLE), established the laws of probability distribution of the duration of train delays for various operations at the railroad station Den Haag HS in the Netherlands. These results could be used when predicting the propagation of train delays, especially in the absence of empirical data. There is a similar study [3] performed for operation conditions of the Ukrainian railroad network, but the results obtained demonstrate a significant error, which is why, when introducing the new train timetable, their representativeness might be compromised.

Study [12] outlines the search for dependences in parameters that describe the process of delay propagation. The authors, based on empirical data from the German railroads (Deutsche Bahn AG), established a function that is characterized by an exponential equation and describes a permissible total length of the queue (LWB) depending on the share of passenger trains in the total number of trains at the subsection. Based on the results of calculations, the authors found threshold values for the total duration of a delay on the railroad network Deutsche Bahn, which ranges from 130 to 300 minutes. However, according to [11], these dependences require further refining; sometimes they describe the actual processes inadequately. The established parameters of dependence satisfy the requirements of operations on the railroads in Germany only, and thus could not be used on the railroad network of Ukraine and those similar to it.

To improve the accuracy in estimating the parameters of train delay propagation on the network, the approaches based on stochastic optimization [13, 14] were employed. The example of software developed in order to study failures in operational work at the macro level of traffic timetable is the NEMO package [15]. An effective approach to the estimation of delay propagation at the macro level of train scheduling is the proposed algorithm for solving a linear system of equations based on max-plus algebra [16]. This algorithm could be applied to large-scale train schedules in real time. However, the application of a given approach to the non-cyclic train scheduling employed on railroads with mixed traffic, including Ukraine, is not possible.

Quite common are the micro-simulation models used in such software as SIMONE [11], RailSys [14], OpenTrack [17], ANKE, VIRIATO, or ATTPS [18], which make it possible to assess the impact of an initial delay on the propagation of the overall delay at a subsection. Though these software packages take into detail consideration the system of alarm and control, they are quite complicated for construction and cannot be applied for large-scale traffic timetables that cover the entire railroad network. It should be noted that in order to avoid these shortcomings, it is a rather popular practice to integrate the software for the micro- and macro levels of simulation, which makes it possible to improve the accuracy of research [19].

In addition to the stochastic uncertainty of the process of delay evaluation, there are methods that make it possible to represent the process of evaluation as a fuzzy uncertainty. Thus, paper [20] proposed, in order to model a delay
propagation in the network, which is represented as an oriented graph, to apply a hierarchical fuzzy system, which consists of fuzzy knowledge bases of the Mamdani type. Though the authors proposed performing the optimization setting of fuzzy rule base parameters, the construction of these rules, however, is a subjective procedure based on expert estimation, and does not make it possible to take into consideration in full all the factors contributing to the occurrence of a delay in the network. In addition, a given approach is difficult to apply to the graph of a railroad network of great dimensionality.

Other transport sectors pay special attention to problems related to studying a delay propagation. There are many studies into delay propagation or congestions in complex networks in space and time performed for automobile transport [21–23].

Papers [21, 22] proposed mathematical models of the delay propagation dynamics in the flow of automobiles, based on the application of methods for modeling kinematic waves. This approach is based on the macroscopic approach and does not make it possible to obtain detailed parameters for the influence of each delay on other vehicles that move in the flow. Research [23] is different in that it employed imitation simulation at the microscopic level, which improves the accuracy of results; this, however, increases complexity of the calculations when tackling problems of large dimensionality.

Attention is also paid to studying the propagation of congestions or delays in air transportation networks. Quite interesting results were obtained in paper [24], which applied a model of the delay propagation dynamics in complex networks of air transport by analogue to modelling the spread of infectious diseases.

Based on the above analysis, studying the propagation of delay of moving units in the flow is given much attention to in all transport sectors. Given the range of research undertaken for railroads with cyclic train scheduling and separated traffic of freight and passenger trains, it becomes clear that there is no any comprehensive approach to thorough investigation of the process of train delay propagation in time and space for railroad networks with mixed traffic of freight heavy-weight and multi-car trains of different categories. There exists no method for the imitation simulation of train delay propagation in a standard train timetable, which makes it possible to conduct modeling for a ramified network of interconnected railroad stations. A statistical analysis is missing that would examine the dynamics of delay propagation process evaluation with respect to the conditions of acting standard train timetable. All the above necessitates conducting the research into this area, which would lay the foundation for the automation of processes to design a standard non-cyclical train timetable.

The aim of present study is to examine the possibility of mathematical modeling of delay propagation in non-cyclical train scheduling on a railroad network with mixed traffic, in order to study the dynamics of delay transfer between trains, which would make it possible to reveal the most vulnerable points in train timetable and to work out compensating measures to improve the reliability of standard train traffic timetable.

To accomplish the aim, the following tasks have been set: 
– to formalize the process of delay propagation in non-cyclical train scheduling for a railroad network with mixed traffic of passenger and freight trains; 
– to study the process of delay propagation for various scenarios in the delay occurrence.

4. Development of a method for modeling the delay propagation in non-cyclical train scheduling on a railroad network with mixed passenger and freight train traffic

4.1. Study of the process of train delays in a traffic timetable

To implement the mechanism for the occurrence and propagation of train delays on a railroad network, it is important to define main components of the actual timetable of trains at subsections. Thus, the actual time of a train movement can be divided into components according to Fig. 1 [25].

According to Fig. 1, the actual train running time along the subsection consists of the scheduled basic running time and delays. In line with UIC [26], the scheduled basic running time (a string) of train consists of the basic running time, a recovery margin, and a supplementary margin. The basic running time, or the minimum train running time along the subsection depends on running qualities of the rolling stock, the characteristics of infrastructure, and permanently enabled restrictions. It should be noted that on the railroads of Ukraine, a station-to-station running time, time of acceleration and deceleration of trains, are set by traction calculations in accordance with the applicable “Rules of execution of traction calculation for train operation” [27], based on the standards of train mass (unified or parallel) and taking into consideration the total capacity of permanently acting, as long as long-term, warnings about speed limits along station-to-station block. The time dependent on train traffic can be defined as the time that is added to the schedule to align the time for overtaking and crossover, as well as for passenger operations.

The time for recovery in a string (recovery margin) is established to compensate for delays, which can be divided into primary delays that occur randomly, and secondary delays that arise from reasons due to the primary delay of the first train and subsequent disruption of timetable of other trains that happen to be in the region of the delayed train [28]. Primary delays are exogenous and may occur for reasons of technical failures in the work of subsystems of the railroad infrastructure (contact network, track, rolling
Control processes

stock), errors in the operational work of dispatching personnel, exposure to weather conditions or interference in the work of railroads by a third party, etc. The number, duration, and sequence of secondary delays depend on the priority of strings of trains, train scheduling saturation, and location of trains of different categories relative to each other. Fig. 2 shows a diagram for rolling out the strings of trains along a two-track subsection in the case of occurrence of a primary delay and secondary delays.

On the railroad network of Ukraine, the accounting of delays is executed based on trains departing the station and their running time, which implies taking disruptions into account in the process when trains run between the stations. Therefore, primary delays have been studied sufficiently enough, and, as an example, in the course of our work a statistical analysis was performed of data on the duration of train delays for the first half of the year 2016 at the regional branch “Southern Railroad” of JSC “Ukrzaliznytsya”. We established continuous laws in the distribution of delay duration for dispatching and running between stations (Fig. 3, a, b). It was found that the duration of delays of both types follow the exponential distribution with indicators: for dispatching $\lambda_1=0.039738$, and $\lambda_2=0.046466$, respectively, for running between stations. Mathematical expectation is, accordingly, $\mu_1=25.17$ min. and $\mu_2=21.52$ min. The proposed hypotheses about the agreement between experimental data and the assigned kind of the probabilistic law were tested for plausibility using the Pearson criterion with a significance level of 0.05.

While primary delays are random, which are almost impossible to avoid and predict, the propagation of secondary delays is an interconnected process, which represents so-called “cascading delay” or a “domino effect” [29]. Therefore, by knowing the train scheduling and duration of the primary delay, it is possible to predict, sequentially, the place and duration of the occurrence of cascade of secondary delays. Under conditions of secondary delay propagation, it is required to anticipate the impact of network effect [30] – there are many routes of trains that pass several railroad sections, which leads to the extraordinary interconnection between train timetable strings. The impact of a delay under conditions of high density of train traffic can spread over long distances and cause traffic jams in different places of the railroad network. Given such conditions, studying delay propagation on the railroad network using mathematical modelling will make it possible to identify the most critical points in the schedule of trains that would enable changes in the timetables of trains in order to reduce the specified consequences of delays.

4.2. Procedure for studying the influence of train delays in non-cyclic train scheduling

To study the impact of the magnitude of initial delay on the reliability of the basic timetable of trains on a railroad network, we devised a procedure the block diagram of which is shown in Fig. 4.
Underlying the procedure is the simulation imita-
tion using an optimization model for the construc-
tion of WTT, which implies generation of the assigned magnitudes of
time of train delays and the station of their occurrence.
Next, the construction of a rational WTT with respect
to failures is performed, and statistical parameters of de-
lay propagation are calculated. These parameters are the
source data to search for the best variant of determining
the magnitude of time reserve with respect to the minimi-
zation of risks of delay.

To model delay propagation in non-cyclic train sched-
uling for different variants of failures, we propose applying
an optimization mathematical model for building a train
timetable, which represents a procedure for rolling out the
strings of WTT along a section as the problem of optimal
allocation of limited resources over time, which in terms of
the scheduling theory can be formalized in accordance with
a flow-shop problem [31, 32]. According to previous study
[33], mathematical model for calculating the schedule of
trains has an objective function:

\[
F = \sum_{j=1}^{J} \sum_{i=1}^{I} c_{\text{train}, \text{beam}}(g_{ij}, -t_{ij} - g_{ij} + \delta_{ij} c_{\text{delay}}) + \\
+ \sum_{i=1}^{I} \max(0, (g_{ij} - D_{ij})), \rightarrow \min,
\]

(1)

and constraints

\[
\begin{align*}
\eta_{ij} &> 0; \eta_{ij} \leq T; i \in I, j \in J; \\
g_{ij} &= g_{ij, \text{start}} + t_{ij} + t_{\text{move}} + \delta_{ij} c_{\text{accel}} - \gamma_{ij}; \\
\varphi &\left( g_{ij} + t_{\text{move}} \leq g_{ij, \text{start}} - t_{ij} \right); \\
\varphi &\left( g_{ij} + t_{\text{move}} + \tau_{\eta_{ij}} \leq g_{ij, \text{start}} - t_{ij} \right); \\
\varphi &\left( g_{ij} + t_{\text{move}} + \tau_{\eta_{ij}} \leq g_{ij, \text{start}} - t_{ij} \right); \\
\varphi &\left( \sum_{j=1}^{J} x_{ij} \leq 1 \right),
\end{align*}
\]

where \( x_{ij} = 1 \) for \( g_{ij} - t_{ij} \leq t < g_{ij} \) and 0 otherwise, \( t \in T, i \in I \);

\[
\eta \left( \sum_{j=1}^{J} x_{ij} \geq 0 \right), i \in I;
\]

\[
\sum_{j=1}^{J} x_{ij} = 1, j \in J;
\]

\( g_{ij} \leq D_{ij} \),

where \( i \) is the number of string along which a train runs,
\( i = 1, 2, ..., m \); \( j \) is the number of subsection along a section,
\( j = 1, 2, ..., n \); \( c_{\text{train}, \text{beam}} \) is the cost of train idling at an inter-
mediate station, UAH; \( g_{ij} \) is the endpoint of train \( i \) at subsection \( j \);
\( g_{ij, \text{start}} \) is the endpoint of train \( i \) at subsection \( j+1 \); \( t_{ij} \) is
the basic running time of the \( i \)-th train along subsection \( j \); \( t_{\text{move}} \)
is the cost of the late arrival of the \( i \)-th train to the station of de-

tination, UAH; \( t_{\text{accel}} \) is the cost of the fine for a late arrival of the \( i \)-th train at the station of
destination, UAH; \( L \) is the section that proceeds the desti-
nation station of the train, \( L = 1, 2, ..., m \); \( D_{ij} \) is the required
time of arrival of the \( i \)-th train from section \( L \) at the station of
destination, min; \( T \) is the period of planning, \( T = 1.440 \) min;
\( t_{\text{move}} \), \( t_{\text{accel}} \) are, respectively, the rated time for acceleration
and braking of the \( i \)-th train along the \( j \)-th section, min;
\( \gamma_{ij} \) is a function where \( \gamma_{ij} = 1 \), if the \( i \)-th train accelerates
along the \( j \)-th section, and \( \gamma_{ij} = 0 \) if a train passes the station
without stopping; \( t_{ij} \) is the interval between trains along the
\( j \)-th section, min; \( \varphi \) is the section’s identifier that accepts a
value of \( \varsigma = 1 \) if it is a one-track section, \( \varsigma = 0 \) for a two-track
section, \( \varsigma \in \{1, 0\} \); \( \eta \) is the identifier of the section that takes
a value of \( \eta = 1 \) if it is a two-track section, \( \eta = 0 \) otherwise,
\( \eta \in \{1, 0\} \); \( \tau_{\eta_{ij}} \) is the station interval crossover, min; \( m; \)
\( \tau_{\eta_{ij}} \) is the station interval of non-simultaneous arrival at the
\( j \)-th section, min; \( x_{ij} \) is a function that accepts a value of \( x_{ij} = 1 \) if at
time point \( t \) section \( j \) is taken by train \( i \), and \( x_{ij} = 0 \) otherwise,
\( \in \{I, J\} \); \( \min t_{ij} \) is a problem of optimal allocation of
limited resources over time, which in terms of
the scheduling theory can be formalized in accordance with
a flow-shop problem [31, 32]. According to previous study
[33], mathematical model for calculating the schedule of
trains has an objective function:

Given the complexity of compiling WTT, it is possible
to accept, to serve as an estimated section for which one
constructs a timetable of trains, both a one-track line and
a two-track line, limited by technical stations that handle
most flows of trains. To solve the mathematical model de-
signed, we applied one of the methods for multi-agent opti-
mization, the Artificial Bee Colony Algorithm (ABC)
[34], which is based on modeling the behavior of bees
in natural environment. The advantage of applying
the ABC algorithm is its better rate in the search for
rational WTT compared to classical methods of
optimization.

To implement the simulation of delay propagation
in train traffic schedule taking into consideration a
network effect, it is proposed to represent the railroad
network of Ukraine in the form of graph \( G(V, U) \) con-
sisting of a set of vertices \( V \) that represent the total-
ity of technical stations at railroad network \( e \in V \), and a set of
edges \( U \) where \( u \in U \) are the railroad sections accord-
ing to the train sections in a standard train timetable.
The estimated section is accepted to be a railroad line
section, which is limited by technical stations (sorting,
subdivision, or cargo-handling that perform the func-
tions of subdivisions). Each section \( U \) can comprise
one-track or two-track sections based on the assigned
identifier \( \varsigma \in \{1, 0\} \) and \( \eta \in \{1, 0\} \).

Given the complexity of automated calculation of WTT
for the entire rail network or a line, we implemented a proce-
dure for the decomposition of section-based calculations by
connecting these sections to the direction of rolling out the
strings in a schedule. The procedure for WTT construc-
tion applied implies rolling out the strings in a timetable ac-

cording to the preset points of departure or arrival of trains
of different categories at the stations of the section. An example
of the connection scheme along a railroad direction using
different modes for rolling out the strings in a timetable is
shown in Fig. 5.

The implementation of rolling out modes makes it
possible to match the calculations of WTT at adjacent
sections according to geographical location. The first sec-
tion can be estimated, in line with the purpose of building
WTT for different rolling out modes: “From both direc-
tions”, “In odd direction”, “In even direction”. For example,
under the mode “From both directions” – trains in odd and even directions are set out from the point of departure in the direction of their basic traffic. For further alignment between through strings in the schedule, the next section is automatically connected to the preceding one under the mode “In odd direction” – trains in the odd direction (top-down running direction) are set from the point of departure. The trains in even direction are set from the point of arrival in the opposite direction to their movement along the section (Fig. 5).

According to the proposed procedure of simulation (Fig. 4), the first stage implies the construction of a standard train timetable for each interconnected section according to the above connecting scheme, and the timetable is kept for further analysis. Upon establishing the station and the duration of the initial delay, the construction of WTT is performed for each station of graph G taking into consideration delayed trains. At the last stage of modeling, in order to conduct a comparative analysis, an algorithm was designed, which automatically compares the standard train timetable with the model scheduling at the section, consistently according to the directions of train flows on the network. The analysis implies the calculation of the number and duration of secondary delays in the timetable.

4.3 Results of the simulation of delay propagation in non-cyclic train scheduling using the line Lyubotin–Sovnarkomivska–Poltava-South–Potoki of the railroad network of Ukraine as an example

According to the developed procedure for studying an influence of train delays in the standard timetable (Fig. 4), we performed simulation of train delay propagation in the timetable on the railroad line Lyubotin–Sovnarkomivska–Poltava-South–Potoki of the Ukrainian rail network, which is part of the direction for the flow of trains from Kharkiv to Kyiv and Odesa. In the course of present research we used data from the standard train timetable for 2013–2014. Graph G of the rail polygon at the regional branch of the Southern Railroad of JSC “Ukrzaliznytsya” (PAT UZ), which includes train sections along the direction Lyubotin–Potoki, is shown in Fig. 6. Operational length of two-track sections is: Lyubotin–Sovnarkomivska – 6.1 km; Sovnarkomivska–Poltava-South – 109.8 km; Poltava-South–Potoki – 101.9 km. Total length of the line is 217.8 km.

A fragment of the standard train timetable in the programming environment Matlab, which was built based on the ABC optimization algorithm’s solution to the developed mathematical model, is shown in Fig. 7.

**Fig. 6.** Graph G of the rail polygon at the regional branch of the Southern Railroad of JSC “Ukrzaliznytsya”, which includes train sections along the direction Lyubotin–Sovnarkomivska–Poltava-South–Potoki
To study delay propagation, it is proposed to simulate the initial delay of two high-speed passenger trains No. 161 and 162, which will run in different directions along the examined line only at sections Lyubotin–Sovnarkomivska–Vakulinci. A given scenario allows us to explore in detail the possibility of transferring the secondary delays to the section Poltava-South–Potoki, which the routes of trains with the primary delay do not pass. Based on the scenario of simulation, we delayed trains Nos. 161 and 162 by 15, 25, and 35 minutes at stations Lyubotin and Vakulinci, respectively. We calculated three variants of the model schedule of trains and performed a statistical analysis of delays along the entire estimated line. As an example, Fig. 8, 9 show dependence of the number and duration of delayed trains with a cumulative total on time of the occurrence of a delay in the timetable for the scenario implying a primary delay of 35 minutes.

Based on the parameters of the delay propagation dynamics, it was established (Fig. 8, 9) that, for the odd direction, the propagation time is 937 minutes, while for the even direction is 256 min, which is 27.3 % less than the time for the opposite direction. The total number of delayed trains is the same. However, for the odd direction, the delay with a cumulative total amounted to 32 minutes, while for the opposite direction the total delay is 2 times longer and reached 103 minutes. Therefore, the delay of train No. 162 at Vakulinci station is the most influential and requires establishing a time reserve in the standard train schedule in order to reduce the impact of a network effect on the operation of several sections along the railroad line.

Fig. 7. Visualization of a fragment of the standard train timetable, which was calculated using the developed mathematical model, based on the solution obtained by applying ABC optimization algorithm in the programming environment Matlab

Fig. 8. Dependence of the number and duration of delayed trains with a cumulative total on time of the occurrence of delays in a timetable for the scenario implying the occurrence of an initial delay for train No.161 by 35 minutes in the odd direction

Fig. 9. Dependence of the number and duration of delayed trains with a cumulative total on time of the occurrence of delays in a timetable for the scenario implying the occurrence of an initial delay of 35 minutes in the even direction
To analyze spatial propagation of delays, Fig. 10 shows a chart of the number and duration of delayed trains relative to the point of delay occurrence in the timetable of trains along the line Lyubotin–Sovnarkomivska–Poltava-South–Potoki for the scenario of delays of trains Nos. 161 and 162 by 35 minutes.

To analyze the dynamics of delay propagation in a train timetable at the examined line, it is proposed to visualize the obtained dependences of delay duration on time of the occurrence of delays in the timetable for three scenarios of the occurrence of a primary delay in a three-dimensional space (Fig. 11).

The obtained results of delay propagation allow us to estimate reliability of the existing standard non-cyclic train scheduling, and make it possible to explore the dynamics of formation of cascading delays. Based on the analysis of data for the impact of interdependence of train traffic in a standard timetable. Expert analysis of the results obtained confirms the relevance of modelling to the actual processes occurring at interdependence of trains in the designed schedule.

5. Discussion of results of applying the developed method of simulation of delay propagation in non-cyclic train scheduling

The obtained results of application of the developed method correspond to the actual processes of the occurrence of disruptions in train traffic and prove the possibility of modeling delay propagation in non-cyclic train scheduling for railroads with mixed traffic using the railroad network of Ukraine as an example. All previous known studies, specifically published in [3, 35] performed analysis based only on statistical processing of empirical data on the number and duration of delays for the fulfilled train schedule in accordance with the periodic reporting from regional branches of PAT UZ. For the conditions of operation of railroads with a non-cyclic train scheduling, under traffic conditions of multi-car and heavy-weight trains, there is a lack of research aimed at modeling delay propagation in an actual standard timetable with detailed patterns of the process in time and space. Obtained dependences of the delay propagation dynamics allowed us to estimate the duration and number of failures in a standard train timetable relative to the initial delay. The research results are preliminary and need further improvement of the simulation mathematical model based on taking into consideration the random character of the process of reducing a delay in the movement of trains by allocating a time reserve and by transforming the problem into a multicriterial one to search for the Pareto-optimal solution. In addition, further research should improve the algorithm's capability to solve problems of large dimensionality.

6. Conclusions

1. We have devised a method for modeling delay propagation in non-cyclic train scheduling for railroad networks with traffic of passenger and heavy-weight or multi-car trains of different categories, which makes it possible to
explore the dynamics of occurrence of secondary delays in the schedule of trains and to estimate the number, point of occurrence, and duration. It is proposed, as a base for the developed method, to apply a mathematical model for the construction of non-cyclic train scheduling based on the multiagent optimization. To account for delay propagation on a railroad network of great dimensionality, we devised a procedure for connecting the interrelated sections, which makes it possible to decompose the general problem on the basis of the construction of a schedule of trains for separate estimated sections taking into consideration a network effect. It allows the automatization of one of the stages in making up a standard non-cyclic train timetable – defining the reserve in a standard train timetable, based on the prediction of consequences of train delays.

2. To analyze the impact of delay duration on the level of reliability of non-cyclic train scheduling, we studied the process of delay propagation for various scenarios of the occurrence of a delay using an example of the line Lyubotin–Sovnakomivska–Poltava-South–Potoki of the Ukrainian railroad network. We performed analysis of the dynamics of propagation of secondary delays in a schedule of trains with detailed examination of changes in all parameters in time and space. The dependences were obtained of the number and duration of delayed trains on the point of occurrence in the train timetable along the estimated line. It was established that for the scenario of the primary delay of 35 minutes, the delay in odd direction with a cumulative total amounted to 52 minutes, while for the opposite direction, the total delay was 2 times longer and reached 103 minutes. This allowed us to conclude that the delay of train No. 162 at Vakulenci station is the most influential and requires allocating a time reserve in the standard train schedule in order to reduce the impact of a network effect on the work of several sections of the railroad line. The simulation results obtained correspond to the actual processes occurring at interdependence of trains when the timetable was fulfilled, which confirms the adequacy of the proposed procedure of simulation to the actual operation conditions of a railroad network with mixed movement of passenger and freight trains of different categories.

References


