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DETERMINING THE RATIONAL MOTION INTENSITY OF TRAIN TRAFFIC FLOWS ON THE RAILWAY CORRIDORS WITH ACCOUNT FOR BALANCE OF EXPENSES ON TRACTION RESOURCES AND CARGO OWNERS

Tetiana Butko [1], ***Mykhailo Muzykin*** [2], ***Andrii Prokhorchenko*** [3], ***Halyna Nesterenko*** [4], ***Halyna Prokhorchenko*** [5]

[1,3,5] *Ukrainian State University of Railway Transport, Feierbakh Sq. 7, Kharkiv, Ukraine*
[2,4] *Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan, Lazyaryan Str., 2, Dnipro, Ukraine*
[1] *uermp@ukr.net*
[2] *mihailmuzykin@gmail.com*
[3] *prokhorchenko@kart.edu.ua*
[4] *halynanesterenko@gmail.com*
[5] *g.o.prokhorchenko@kart.edu.ua*

The article proposes a method for determining the rational motion intensity of specific train traffic flows on railway transport corridors with account for balance of expenses on traction resources and cargo owners. A mathematical model based on stochastic optimization is developed, which allows to optimize, in the conditions of risks, the interval between trailing trains on the railway lines taking into account the limited resources of the traction rolling stock, the capacity of the stations and freight fronts at the cargo destination point. Solving this mathematical model allows to find a balance between the expenses for movement of train traffic flows from different railway lines to their terminal reference station and the expenses of a consignee, subject to the limitations of the technological logistics chain in cargo transportation. For the solution of this mathematical model, a Real-coded Genetic Algorithm (RGA) was used.

Keywords: railway network, transport corridor, train traffic flow, traction rolling stock, risks, stochastic optimization, genetic algorithm

1. Introduction

The choice of interval between trains in the flow is important for more economical and quick passage of each individual train traffic flow. From the chosen interval between the train movement on the railway direction depends both the value of the required locomotive fleet and locomotive crews for its maintenance, and the total expenses of the consignees at the terminal stations of the route. In conditions of rising deficit of the traction rolling stock and the high cost of energy, the expenses of PJSC "Ukrainian Railways" (PJSC UZ, Kyiv, Ukraine) for the movement of train traffic flows become comparable to the ones incurred by the consignees at the terminal stations of routes due to the change in the cargo delivery interval (demurrage in ports, expenses for unbalanced process of transhipping cargo for its further movement for export, etc.).

After determining the patterns of locomotive circulation and locomotive crews (Butko *et al.*, 2016), it is important at the development stage of the tight run profile to set the intervals of the specific trains in the freight direction. This will create conditions for the development of the trains schedule that is more adapted to the real operating conditions of the railway network and the needs of consignees. The task of finding the time for arrival of trains from different railway corridors to the terminal (reference) station of the routes for the further cargo transhipment to other modes of transport, taking into account the restrictions for traction equipment, is a rather complicated optimization problem (Caris *et al.*, 2008; Ferreira, 1997; Bektas and Crainic, 2007; Caprara *et al.*, 2011; Talebian and Zou, 2014). This complexity is due primarily to the uncertainty of the movement processes of trains over long distances and the operation of freight fronts for unloading or cargo transhipment, which greatly complicates the planning procedure.

The conducted research in paper (Kasalica *et al.*, 2013) concerning the cyclic locomotive assignment planning in the trains schedule prove the effect of interval value between trains, which varies from the causes of delays, on the size of the locomotives fleet. It is proposed to take into account statistics upon actual train delays when planning the number of locomotives, and the results of this study showed that it is possible to achieve significant efficiency of using the locomotives with schedule improvement. The coordinated operation of the main marshalling yards and terminals of seaports has a major impact on the speed of trains through the railway corridors. In the papers (Bostel and Dejax, 1998; Zhao *et al*., 2018), the efficiency of taking into account the stochastic processes in the maintenance work of intramodular transport corridors and container terminals in ports is proved.

In many research, when planning the operation of railway corridors at the tactical level, consideration of tasks, related to the plan of locomotive fleet operation is considered as one of the isolated planning stages. The paper (Powell *et al.*, 2012) is devoted to the planning of locomotives at the strategic and tactical levels on the Norfolk Southern railway. In paper (Nahapetyan *et al.*, 2007) it is proposed a decision support system named LSO - Locomotive Simulater/Optimizer, which allows simulating the locomotive movement with four components - Trains, Locomotives, Terminals, and Shops in an integrated environment. Studies devoted to the scheduling of locomotives can be found (Su *et al.*, 2015). This paper solves the task to optimize the scheduling of locomotives, taking into account the volumes of transportation on the double-track electrified line Da-qin Railway. In the above-mentioned scientific papers, there are no research that allow taking into account the mutual influence of the efficiency of a locomotive fleet with regard to the operating conditions in the work of the reference marshalling yards and connected with them port terminals (Pedersen and Crainic, 2007). However, in studies devoted to the development of intramodular transport corridors, more and more attention is being paid to the construction of integrated mathematical models (Zhu *et al.*, 2014; Crainic and Kim, 2006; Macharis and Bontekoning, 2004), which allow taking into account the characteristics of each individual train traffic flow, the operation of railway terminals and ports, with regard to the generalization of the interests of all participants in the transport process.

The above analysis proves the lack of a holistic approach to formalizing the technology of the railway corridor operation, taking into account the bulk transport, not being transported in containers, and requires the reorganization actions at a marshalling yard and has a significant degree of uncertainty in the time of loading/unloading operations in ports. In addition, research is almost undeveloped which allows taking into account in the logistics chain the cargo delivery on the railway corridor the available limited locomotive fleet on the direction. All this requires necessary research in this field, which is the basis for automation of planning processes.

2. Methodological Approach

In the framework of setting the task for the passage of a specific train traffic flow on the railway lines, it is envisaged to use a group schedule for servicing locomotives of trains on found locomotive hauls. According to this approach, a separate group of locomotives serves only specific trains of destination to the terminal station of the corridor. This will accelerate the speed of trains on the railway corridor. In such conditions, for each railway route, the time interval between the trailing trains in "freight direction" is the determining factor (Sivilevičius, 2011; Kasalica *et al.*, 2013), its value determine the expenses for locomotives running and their required amount. In the general, this problem on the railway network can often be represented as an adjoining of several railway lines to the terminal marshalling yard, which is the station of cars scattering (the reference station can be the port or border station, where there is a change from a gauge width of 1520 mm to 1435 mm). As an example in this study, it is proposed to consider the option of arriving the car traffic flow to the seaport. Schematic representation of this option is shown in Figure 1.

Let us consider the situation of risk management in the process of logistics chain when passage of car traffic flow through the railway corridors (Chen and Schonfeld, 2012), when it is necessary to determine the arrival time of trains from different lines subject to the following restrictions: the size of existing operational fleet to service specific train traffic flow; the capacity of the reference station and stations adjacent to it and taking into account the operating regime of the loading/ transhipping fronts.

Considering that the real conditions of the train traffic flow on the railway lines and conditions of operation for the loading/ transhipping fronts are not homogeneous and are stipulated by a large number of factors, that are difficult to foresee in the study, we propose to present the solution of the problem posed in the form of optimization in stochastic statement with regard to the arrival time of trains and the time of cars arrival to the consignee at the unloading/ transhipping front in a random environment (Quaglietta *et al.*, 2013).

In order to assess the uncertainty, it is suggested to use the concept of risk – estimation of prospective expenditures associated with uncertainty in the processes of trains movement on the railway lines, the work of the port stations and loading/transhipping fronts. Thus, the task of constructing the mathematical model arises. It allows, in the conditions of risks, to optimize the arrival time of trains on the basis of statistical data for previous periods regarding the deviations of the arrival time of trains to the terminal station from the normative indicators and the time of arrival for cars from these trains to the consignee at the unloading/transhipping fronts.

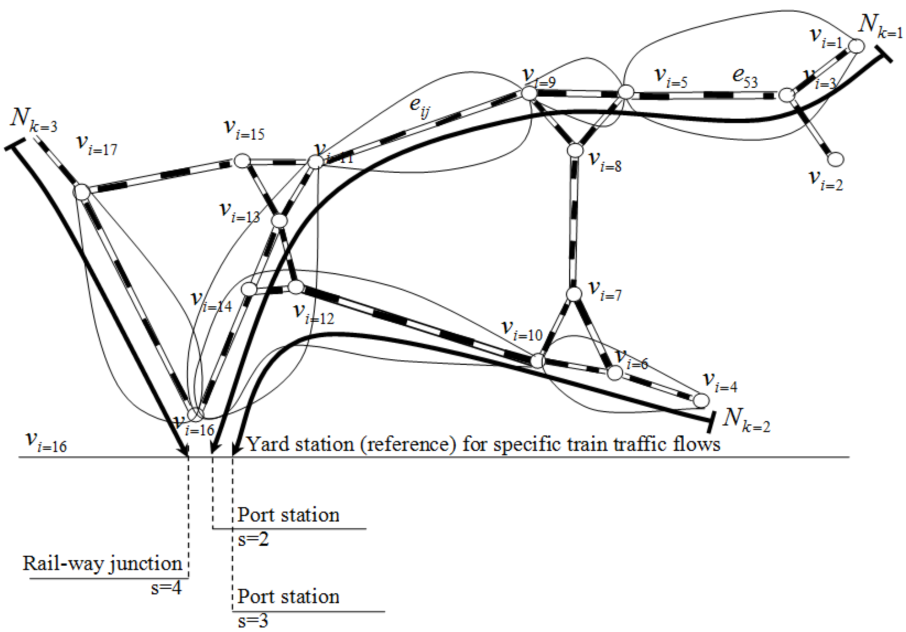

Figure 1. Scheme of movement of specific train traffic flows according to certain hauls of locomotive circulation to the reference technical station with the designated terminal stations of the car groups

To construct this mathematical model, it is necessary to introduce and describe its parameters. According to the calculations, performed with the help of the mathematical model developed in (Butko *et al.*, 2016), the given parameters are the number of trains from each line k, for which it is necessary to determine the time of arrival $t_{k,0}^{i}$ to the terminal station of routes $N=\sum_{k} N_k$, where k – is the serial number of the railway line on the network, $k=\overline{1,K}$. Considering that the specific freight traffic flow is most often the block train shipment, consisting of one or several groups of cars, this fact should be taken into account when setting the task. Thus, to every thread of the train N_k^i, where $\sum_{i} N_k^i = N_k$, corresponds a set of cars $m_k^i=\sum_{a} m_{k,s}^{i,a}$, where $\sum_{i} m_k^i = m$, a – the number of cars group in the set of thread *i*, $a=\overline{1,A}$, A – the number of cars group in the train N_k^i; s – destination station $s=\overline{1,S}$, according to which determines the final arrival of the corresponding cars group when the train's coming to the reference station of the route s. The graphic model of the choice for the arrival time of trains to the terminal station of routes from different lines in the conditions of uncertainty is presented in the Figure 2.

For the reference station, the planning interval is divided into periods that are limited by the arrival time of specific trains t_i, t_{i+1}, t_{i+2},…, $t_{i=N}$ from all calculational lines, hence, the number of periods is $N-1$. To simplify the designation of periods, one should introduce index p – sequentially numbered moments of the arrival time of trains from different lines to the reference station $s=1$, $p=\overline{1,N}$.

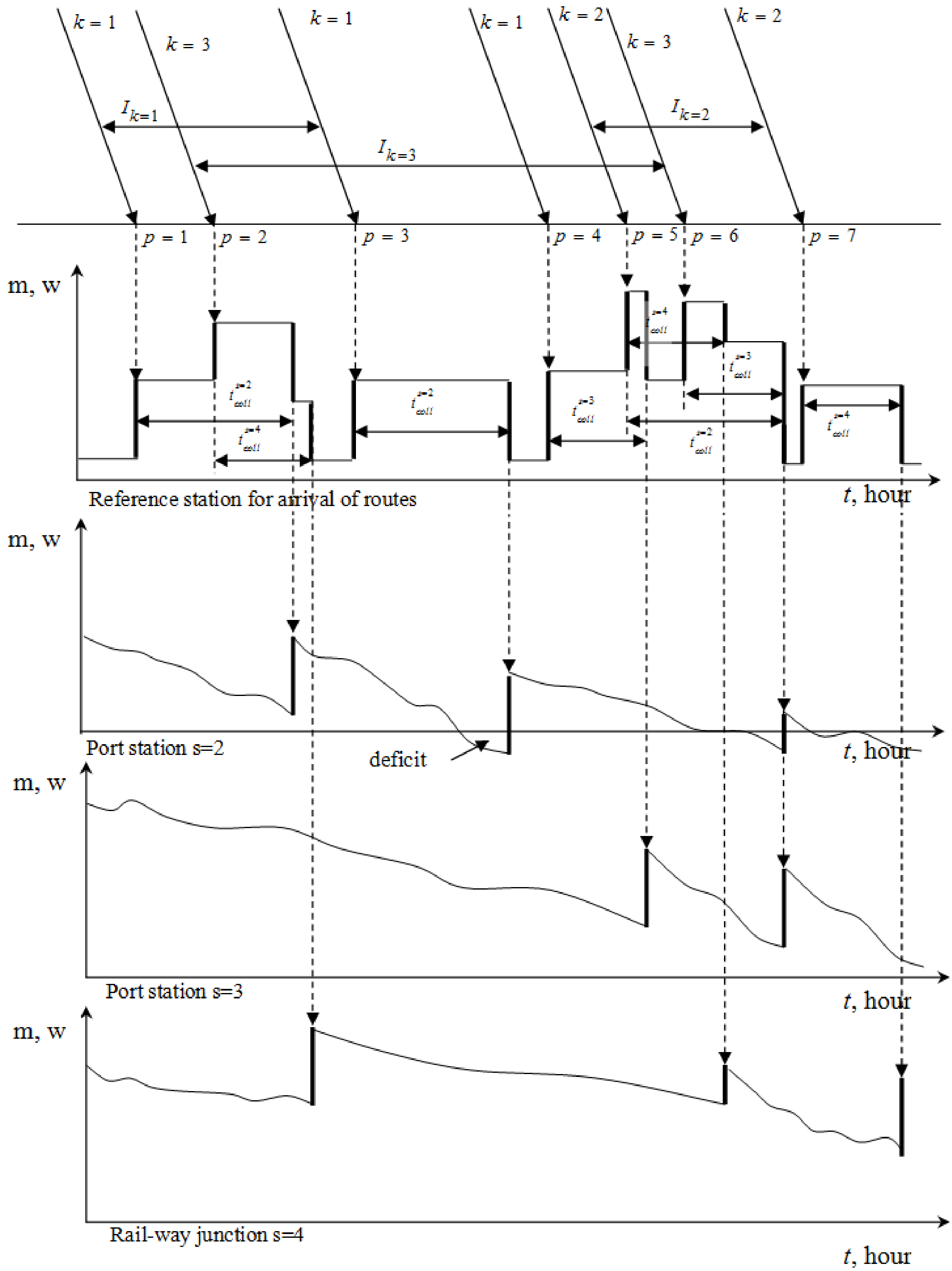

Figure 2. The graphic model of the choice for the arrival time of trains to the terminal station of routes from different lines in the conditions of uncertainty

According to the developed technology for the passage of specific car traffic flows for each railway direction the value of the train, arriving to the reference station $s=1$, is fixed m_k^i and predetermine by the mathematical model developed in paper (Butko *et al.*, 2016). Based on the technology of coordination the operation of the reference station with port stations and the seaport it has been established the standard time for collecting a group of cars $m_{k,s}^i$ to the port station $s=\overline{2,S}$, $m_k^i = \sum_{s=\overline{2,S}} m_{k,s}^i$. Let us introduce the standard time for collecting cars from the reference station to the port one as a value $t_{coll}^{s=\overline{2,S}}$, hour.

In the context of the considered problem, it is proposed to present the uncertainty of the process of specific train arrival to the reference station, as a random process with pre-set parameters. Let us consider the arrival time of trains $t_{k,0}^i$ to the reference station $s=1$ as the value with the normal law of time deviation from the standard arrival time. So, the arrival time of the train to the reference station can be written as follows

$$t_{k,0}^i = t_{k,0}^{i,norm} \pm \Delta t_{k,0}^i, \tag{1}$$

where: $t_{k,0}^{i,norm}$ – the expected time of the train arrival to the station (a variable parameter of the mathematical model), hour; $\Delta t_{k,0}^i$ – random deviation. According to the research (Hruntov *et al.*, 1994, Badetskiy, 2013) it is assumed that the random variable $\Delta t_{k,0}^i$ follow the normal distribution law with density $\varphi(\Delta t_{k,0}^i)$.

Taking into account that quite a lot of random factors affect the time of collecting the cars from the reference station, it can be assumed that the standard time of collecting the cars is also random. Thus, one can write $t^i_{m^i_{k,s=\overline{2,S}}}$ – the moment of collecting the cars $m_{k,s}^i$ from the reference station to the port stations $s=\overline{2,S}$ or to the unloading/transhipping fronts of the port in case of direct option. Existing uncertainty regarding the time of collecting the cars from the reference station to the unloading/transhipping fronts can be determined by the expression

$$t^i_{m^i_{k,s}} = t^{i,coll}_{m^i_{k,s}} \pm \Delta t^i_{m^i_{k,s}}, \tag{2}$$

where: $t^{i,coll}_{m^i_{k,s}}$ – an hour, which is expected to collect cars from the station $s=1$ (standard value established by a single technological process of a railway junction and a port or approach lines of other enterprises), hour; $\Delta t^i_{m^{i,a}_{k,s=1}}$ – random deviation. Taking into consideration the large number of factors affecting the deviation in the time of collecting the cars from the reference station, the study highlights the distribution density of this value under the normal distribution law with given parameters.

The task of finding the optimal time of arrival for each train to the reference station of the route is directed to the convergence of two random processes to one. However, in the conditions of the various factors impact and restrictions, each of the random processes has its own distribution parameters and is independent, which leads to different combinations of situations: advance in the arrival time of the train and the advance in the process of collecting the cars from the reference station to the unloading/transhipping fronts leads to various consequences (Aleksandrov and Yakushev, 2006).

To construct a target function of a mathematical model for determining the intervals between the arrival of specific trains from different lines, it is necessary to evaluate the risks taking into account all situations of occurrence of these events.

One of the component in expenses that should be taken into account in the overall chain of cargo delivery to the consignee is the common car-hours of car detention arriving in specific trains to the reference station $s=1$. In order to determine these expenses, it is necessary to set the idle time on the reference station for each group of cars arriving in the specific trains. The idle time (time interval) can be defined as the difference between the moments of collecting the cars at the appropriate port station and the arrival of the specific train by the expression

$$It_k = (t^{i,coll}_{m^i_{k,s}} \pm \Delta t^i_{m^i_{k,s}}) - (t^{i,norm}_{k,0} \pm \Delta t^i_{k,0}) = It^o_k \pm (\Delta t^i_{m^i_{k,s}} - \Delta t^i_{k,0}) = It^o_k \pm \Delta It_k \,, \tag{3}$$

where: $It_k -$ deterministic time period, for which cars of the group $m^i_{k,s}$ stand idle, $It_k = t^{i,coll}_{m^i_{k,s}} - t^{i,norm}_{k,0}$, hour; $\Delta It_k -$ random component, which is defined as the difference between two random variables $\Delta It_k = \Delta t^i_{m^i_{k,s}} - \Delta t^i_{k,0}$, hour. Considering that random variables $\Delta t^i_{m^i_{k,s}}$ and $\Delta t^i_{k,0}$ follow the normal distribution law with the corresponding distribution densities, then, by the rules of operations over random variables, one can find the distribution density of a random variable ΔIt_k according to the composition rule. So, for the random variables $\Delta t^i_{m^i_{k,s}}$ and $\Delta t^i_{k,0}$ distribution densities have a view:

$$\varphi_1(\Delta t^i_{k,0}) = \frac{1}{\sigma_1\sqrt{2\pi}} \exp \cdot \left[-\frac{t^i_{k,0}}{2\sigma_1^2} \right], \tag{4}$$

$$\varphi_2(\Delta t^i_{m^i_{k,s}}) = \frac{1}{\sigma_2\sqrt{2\pi}} \exp \cdot \left[-\frac{t^i_{m^i_{k,s}}}{2\sigma_2^2} \right], \tag{5}$$

where: $\sigma_1 -$ root-mean-square deviation in the arrival time of the train to the reference station from the standard (planned) value; $\sigma_2 -$ root-mean-square deviation in the time of collecting the cars $m^i_{k,s}$ from the reference station from the standard (planned) value; $t^i_{k,0} -$ current time of the arrival time of the train to the reference station $s = 1$, hour; $t^i_{m^i_{k,s}} -$ current moment of collecting the cars to the port station, hour.

Using the rule for subtraction of distribution density of random variables (Sveshnikov, 1968), one can write distribution density $\varphi_3(\Delta It_k)$ for the value ΔIt_k

$$\varphi_3(\Delta It_k) = \varphi_1(\Delta t^i_{k,0}) - \varphi_2(\Delta t^i_{m^i_{k,s}}),$$

$$\Downarrow$$

$$\varphi_3(\Delta It_k) = \varphi_1(\Delta t^i_{k,0}) + (-\varphi_2(\Delta t^i_{m^i_{k,s}}))$$

$$\Downarrow$$

$$\varphi_3(\Delta It_k) = \frac{1}{\sqrt{\sigma_1+\sigma_2}\sqrt{2\pi}} \exp \cdot \left[-\frac{\Delta It_k{}^2}{2(\sigma_1+\sigma_2)} \right], \tag{6}$$

where: $\varphi_3(\Delta It_k) -$ distribution density in deviation time of car detention at the reference station from standard values; $\Delta It_k = \Delta t^i_{m^i_{k,s}} - \Delta t^i_{k,0}$, hour.

The total cost of car detention at the reference station in waiting for collecting to the port stations or the cargo fronts of the port can be determined by the expression

$$F_1 = \sum_k \sum_i \sum_s \left[C_1 \cdot m^i_{k,s} \cdot \int_{-\infty}^{\infty} It_k \cdot \varphi_3(\Delta It_k) d\Delta It_k \right], \tag{7}$$

where: $C_1 -$ a single cost rate of price for one car-hour in in idle time at the reference station, UAH.

The next expected expenses that should be considered when constructing the target function are the risks of accumulating excess cars at the port stations or the unloading/transhipping fronts and the risks of the so-called deficit - when the cargo fronts are idle due to the lack of cars for unloading. This is explained by the simple situations that may arise in the process of coming the groups of cars to the port stations and collecting them at the berth of the port for loading in to the vessels.

Let's consider the situation of coincidence in deviations of two processes. With the early arrival of cars and the early arrival of the vessel to the port for their unloading, the expected value of expenses decreases. However, depending on the value of advance for each of the processes, there arises both the expenses of cars detention and the additional damage by the lack of cars delivery for unloading (vessel detention without loading). A similar nature of the risks arises when there is coincidence of the delay in the timing of cars arrival and readiness time of the vessel for cargo operations, namely, their collecting to the port. Let us introduce the parameter $t^{i}_{m^{i,port}_{k,s}}$ − time of collecting the cars from the port station to the seaport, that is described as a value $t^{i}_{m^{i,port}_{k,s}} = t^{i,0}_{m^{i,port}_{k,s}} + \Delta t^{i}_{m^{i,port}_{k,s}}$, $t^{i,0}_{m^{i,port}_{k,s}}$ − the expected moment of collecting the cars to the port, hour; $\Delta t^{i}_{m^{i,port}_{k,s}}$ − the random value in the deviation of the expected collecting time with zero mathematical expectation.

Significantly greater losses occur in the case of mismatch of deviations behaviour in two random processes. At an early arrival of the group of cars to the port station ($t^{i,coll}_{m^{i}_{k,s}} - \Delta t^{i}_{m^{i}_{k,s}}$) and delay in collecting the cars to the port due to vessel's inability to load ($t^{i,0}_{m^{i,port}_{k,s}} + \Delta t^{i}_{m^{i,port}_{k,s}}$) expenses arise for cars detention. A similar nature of the risks arises when the arrival of a group of cars is delayed ($t^{i,coll}_{m^{i}_{k,s}} + \Delta t^{i}_{m^{i}_{k,s}}$) and early collecting the cars to the port ($t^{i,0}_{m^{i,port}_{k,s}} - \Delta t^{i}_{m^{i,port}_{k,s}}$).

As already noted above, for the analytical record of total losses, it was assumed that two random events of the arrival of the group of cars to the port station and collecting ones from stations to the port are independent. Since the random variables, subordinating to the normal distribution law, have the feature of stability to the ratio of the composition of the distribution laws, then algebraically according to (Sveshnikov, 1968; Proschan and Shaw, 2016) these expenses can be written as

$$F_2^{s,i,k} = \int_{-\infty}^{\infty} \left[\int_{-\infty}^{t^{i}_{m^{i,port}_{k,s}} - t^{i}_{m^{i}_{k,s}}} C_2 \cdot m^{i}_{k,s} \cdot \left(t^{i}_{m^{i,port}_{k,s}} - (t^{i,coll}_{m^{i}_{k,s}} - \Delta t^{i}_{m^{i}_{k,s}}) \right) \cdot \phi_4 (\Delta t^{i}_{m^{i}_{k,s}}) d \Delta t^{i}_{m^{i}_{k,s}} + \int_{t^{i}_{m^{i,port}_{k,s}} - t^{i}_{m^{i}_{k,s}}}^{\infty} C_3 \cdot \frac{m^{i}_{k,s}}{\Delta t^{i}_{k,0}} \cdot \left((t^{i,coll}_{m^{i}_{k,s}} + \Delta t^{i}_{m^{i}_{k,s}}) - t^{i}_{m^{i,port}_{k,s}} \right) \phi_4 (\Delta t^{i}_{m^{i}_{k,s}}) d \Delta t^{i}_{m^{i}_{k,s}} \right] \cdot \phi_5 (\Delta t^{i}_{m^{i,port}_{k,s}}) d \Delta t^{i}_{m^{i,port}_{k,s}} , \quad (8)$$

where: C_2 − the single cost rate of price for one car-hour in idle time at the port station $s = \overline{2,S}$, UAH.; C_3 − single cost rate of price for one hour in cargo front detention without cars taking into account vessel detention, UAH.; $m^{i}_{k,s}$ − the number of cars in the group of cars, destination to $s = \overline{2,S}$, weight; $\phi_4(\Delta t^{i}_{m^{i}_{k,s}}), \phi_5(\Delta t^{i}_{m^{i,port}_{k,s}})$ − distribution density of the random value in the time deviation respectively the arrival of the group of cars to the port station $s = \overline{2,S}$ and their collecting (the normal distribution law).

For all groups of cars and stations $F_2^{s=\overline{2,S}}$ is written as a component of the general target function by expression

$$F_2 = \sum_k \sum_i \sum_{s=\overline{2,S}} F_2^{s,i,k} \quad . \tag{9}$$

The following risks, which should be taken into account when choosing the interval of trains movement by railway, are working expenditures for the operation of the locomotive fleet. It is proposed to determine these expenditures according to the method of (Nekrashevich and Kudryashev, 2005), which takes into account the dependence of expenses of locomotive-hours from the interval between trailing trains traveling in the railway direction.

Consequently, expenses for locomotive running on the established hauls of their rotation can be determined by the expression

$$F_3 = \sum_k^K C_3 \cdot \left(24 \cdot \frac{\theta_k}{I_k} + TL_{add}^k \right), \tag{10}$$

where: $C_3 -$ the single cost rate of price for one car-hours, UAH.; $\theta_k -$ calculated locomotive circulation for pair of trains, hour; $^{2}{}_{\hat{e}} -$ the interval between trailing trains traveling on the railway direction, hour; $TL_{add}^k -$ additional expenses of locomotive-hours due to reasons of the difference between the end time in the technological operations and the interval of departure of specific freight trains, as well as the arrival and departure irregularity of freight trains due to passage of passenger ones, namely, due to delays of locomotives at points of turn-round, loc-hours.

Considering that the interval between trains is the difference between two moments of arrival of the second and first trains, deviations of which are random variables, and then the value of the interval can be considered as a component of the deterministic time and the random component of its deviation by expression

$$I_\kappa = (t_{k,0}^{i=2} \pm \Delta t_{k,0}^{i=2}) - (t_{k,0}^{i=1} \pm \Delta t_{k,0}^{i=1}) = I_{k,0} \pm (\Delta t_{k,0}^{i=2} - \Delta t_{k,0}^{i=1}) = I_{k,0} \pm \Delta I \ , \tag{11}$$

where: $I_{k,0} -$ a certain interval between trailing trains on the railway direction k, which is determined on conditions $t_{k,0}^{i=2} > t_{k,0}^{i=1}$ as the difference between the arrival time of two trains $^{2}{}_{k,0} = t_{k,0}^{i=2} - t_{k,0}^{i=1}$, hour; $\Delta I -$ the random value of the deviation time of the standard interval between trains, hour. The distribution density is determined as the difference between the two distribution densities of random variables with the normal distribution law by expression $\Delta I = \Delta t_{k,0}^{i=2} - \Delta t_{k,0}^{i=1}$. Taking into account that the normal distribution law has the feature of stability to the composition of two random variables, then the distribution density of the time intervals in deviation from the standard interval between the trailing trains on the railway direction also obeys the normal distribution law (Proschan and Shaw, 2016).

Additional expenses of locomotive-hours in operation for a railway direction with several traction hauls also depend on the interval between trains and can by determined by expression

$$TL_{add}^k = \sum T_{add}^k + 12 \cdot \Pi \ , \tag{12}$$

where: $\sum T_{add}^k -$ total additional locomotive delays at all turn-round points on the railway direction, hour.

The delay data are determined by expression

$$\sum T_{add}^k = \frac{24 \cdot \kappa_c - \sum t_{cm} + 2N(t_{o\delta} + \varepsilon_n \cdot I_n - I_k)}{I_k} \cdot \left[(\varepsilon_n + 1) \cdot I_n - I_k \right], \tag{13}$$

where: $\kappa_f -$ uniformity factor of lining on the schedule of passenger trains; it may be tentatively determined by expression $\kappa_f = 0.8 + 0.2 \cdot N_n$, where $N_{\ddot{\imath}} -$ a number of pairs of passenger trains per day on the traction haul, pairs of trains; $\sum t_{par} -$ total time of parking of passenger trains at the locomotive circulation point, hour (it is determined in accordance with the established norms in the technological process of the operation for each railway station where there is the locomotive circulation within the corresponding railway direction), hour; t_{tr} – normative time of the turn-round on the traction haul, hour; $\varepsilon_{ї} \cdot {}^{2}_{ї}$ – time of collecting the cargo trains by passenger ones, hour; Π – the number of the turn-round on the railroad direction. Scheme for determining locomotive-hours on the railway line k is shown in Figure 3.

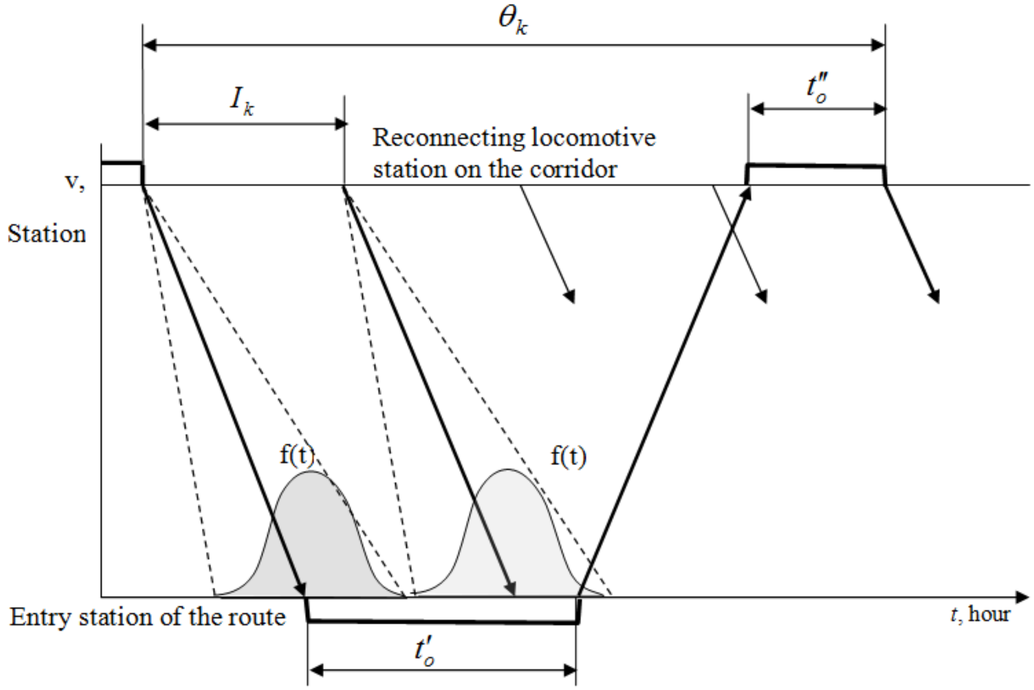

Figure 3. Scheme of movement of specific train traffic flows according to certain hauls of locomotive circulation to the reference technical station with the designated terminal stations of the car groups

3. Construction of an Optimization Mathematical Model

In general, an optimization mathematical model for determining the interval of time between the movement of specific freight trains on the railway direction in the conditions of the random nature in the process of transportation can be written as a target function. It estimates the amount of expenses for penalties for unproductive detentions of loading/transhipping fronts, expenses of excess cars detention on the reference marshalling yard and the port stations, taking into account the interaction with the port, and expenses for locomotives circulation with regard to the rate of specific trains movement on railway lines

$$F_{gen} = F_1 + F_2 + F_3 \rightarrow \min, \tag{14}$$

$$\Downarrow$$

$$F_{gen} = \sum_k \sum_i \sum_{s=2,S} \left[\left[C_1 \cdot m^i_{k,s} \cdot \int_{-\infty}^{\infty} It_k \cdot \phi_3(\Delta It_k) d\Delta It_k \right] + F_2^{s,i,k} + \right.$$
$$\left. + C_3 \cdot \left(24 \cdot \frac{\theta_k}{I_k} + TL^k_{add} \right) \right] \rightarrow \min, \tag{15}$$

with restrictions:

- on the capacity of the reference station (the value of the cars volumes arriving at the station at every moment t should not exceed the maximum capacity of the station)

$$m_0^{s=1} + m_k^i(t) - m_{k,s}^{i,a}(t) \le M_{s=1}(t) \text{,} \tag{16}$$

where: $m_0^{s=1} -$ the number of cars at the beginning of the planning period at the station $s=1$ (rest of cars before gathering at the beginning of the day), weight; negative value $m_{k,s}^{i,a}(t) -$ corresponds to the number of cars at every moment t, that collect from the reference station to the port ones, weight;

- on the capacity of the port stations

$$m_0^{s=\overline{2,S}} + m_{k,s=\overline{2,S}}^i(t) \le M_{s=\overline{2,S}}(t) \text{,} \tag{17}$$

where: $m_0^{s=1} -$ the number of cars at the beginning of the planning period at the station $s=\overline{2,S}$ (rest of cars before gathering at the beginning of the day), weight; $m_{k,s=\overline{2,S}}^i(t) -$ corresponds to the number of cars at every moment t, that collect from the reference station to the port ones, weight;

- the value of the interval between the trains should not exceed the maximum given value according to the technological limitations of the railway operation and the minimum possible interval between trains taking into account traffic safety

$$I_k^{\min} \le I_k \le I_k^{\max} \text{,} \tag{18}$$

where: $I_k^{\min} -$ the minimum possible interval between trains with regard to traffic safety, hour; $I_k^{\max} -$ the value of the maximum possible interval between two trailing trains, given according to the technological limitations in the operation on the railway direction, hour.

- on the size of operational locomotive fleet on the railway direction, which can be used for group servicing of specific freight trains on the railway direction

$$M_k^{loc}(I_k) \le M_{k,\max}^{loc} \text{,} \tag{19}$$

where: $M_k^{loc}(I_k) -$ the value of the required locomotive fleet for servicing of specific freight trains on the railway direction k taking into account the set interval of movement between trains I_k, loc-day. It is determined

$$M_k^{loc}(I_k) = M_{k,main}^{loc}(I_k) + M_{k,add}^{loc}(I_k) \text{,} \tag{20}$$

where: $M_{k,main}^{loc}(I_k) -$ the main need in locomotives on the railway direction in accordance with the defined interval of movement between trains I_k, $M_{k,main}^{loc}(I_k) = \dfrac{\theta_k}{I_k}$, loc-day; $M_{k,add}^{loc}(I_k) -$ an additional need in locomotives caused by the difference in the time of completion of technological operations with the interval of departure for freight trains, as well as the irregularity of arrival and departure of freight trains through the passage of passenger ones, namely, with delays at turn-round points, $M_{k,add}^{loc}(I_k) = \dfrac{\sum T_{add}^k}{24} + 0.5 \cdot \Pi$, loc-day; $M_{k,\max}^{loc} -$ maximum value of the operational locomotives fleet on the railway direction, which can be used for group servicing of specific freight trains, loc-day.

4. The Optimization Procedure Based on the Genetic Algorithm

To solve the mathematical model of stochastic optimization (15-20), authors suggest to use a Real-coded Genetic Algorithm, (RGA) (Herrera *et al.*, 1998). This class of genetic algorithm involves the operating with the vector-chromosomes in the form of real numbers, that is, the genotype is identical to the phenotype of the problem.

At the initialization stage options of solving the mathematical model are presented as a chromosome $\acute{I}$. Chromosome H_s, s=$\overline{1,S}$ is a gene combination, where genes $a_{s,k,j}$ simulate the variable model – $I_{k,j}$

– the interval value j between trains, that arrival from the direction k. The graphical form of the chromosome $H_s = \{a_{s,k,j}\}$ as a vector of real numbers is presented in Figure 4.

$H_{s=1}$

$a_{s,k=1,j=1}$	$a_{s,k=1,j=2}$	● ● ●	$a_{s,k=1,j=J}$	● ● ●	$a_{s,k=2,j=J}$	$a_{s,k=K,j=J}$

Figure 4. Scheme of chromosomes Hs

The value of each gene in the chromosome $H_s = \{a_{s,k,j}\}$ is limited by interval $[I_k^{\min}; I_k^{\max}]$.

The random variables are generated at each iteration of the RGA, following that within the fitness function a sequential calculation of the technological process concerning the arriving the groups of cars on the station's tracks is carried out, collecting to the port station and load on the vessel is performed. The entire process of cars handling on the reference railway lines and expenses for the locomotive fleet are estimated with the help of fitness function, representing the mathematical model (1-6) in the form of unconditional optimization

$$\text{Fitness}(h) = (F_1 + F_2 + F_3) + \lambda\left(\sum_{\psi=1}^{\phi}(\max(0, g_\psi(x)))^2 + \sum_{\kappa=1}^{z}(h_\kappa(x))^2\right) \to \min, \tag{21}$$

where: λ – penalty function parameter, $\lambda > 0$; $g_\psi(x)$ – restrictions of equality, reduced to the form $g_\psi(x) = 0, \psi \in \Psi$; $h_\kappa(x)$ – restrictions for the inequality of the problem, reduced to the form $h_\kappa(x) \le 0, \kappa \in K$.

According to the proposed approach in solving the mathematical model, experimental calculations for solution the conditional practical problem were carried out.

Two different optimization scenarios based on the same traffic volumes and infrastructure parameters were performed for conducting research on different operating conditions of railway corridors: - the first scenario with the source data of distribution laws parameters, approximately correspond to the actual operating conditions of the railway corridors, reference marshalling yards and port terminals (root-mean-square deviation in the arrival time of the train to the reference station from the normative value is 1.4 hours); - the second scenario with the source data of distribution laws parameters that correspond to the punctuality of the trains arrival from the railway corridor with a delay of no more than 30 minutes.

Visualization of the results of solving the mathematical model using RGA with the source data of the first scenario is shown in Figures 5 and 6. In two scenarios it is assumed that by technical equipment, a reference marshalling yard has three tracks in which collecting the cars is carried to three port stations, having port terminals for unloading the cars.

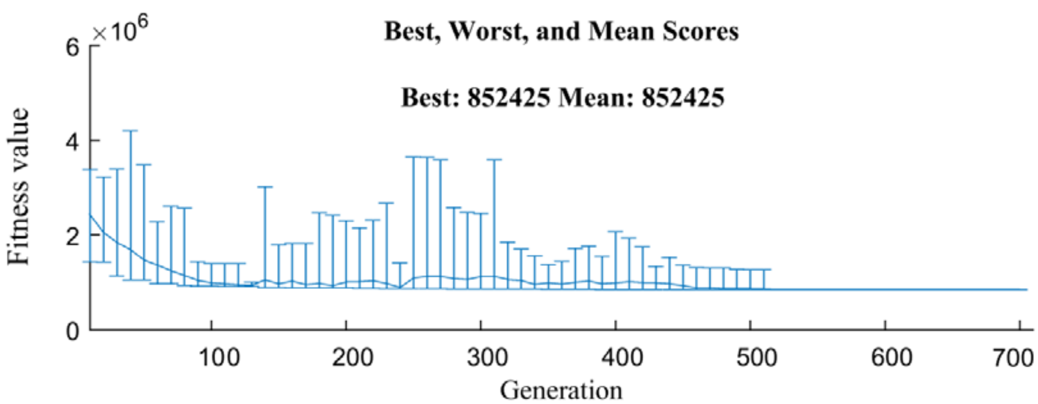

Figure 5. The dependency graph of the best and medium values of the fitness function from the number of RGA iterations in the process of finding a solution

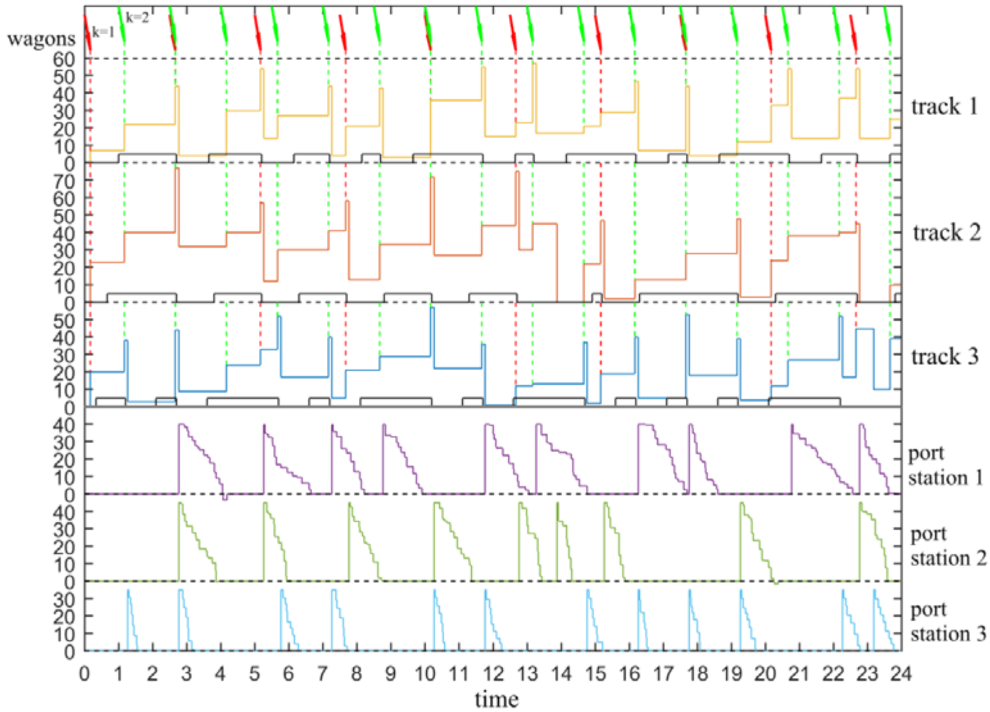

Figure 6. Visualization of a rational plan for cars handling when arriving to the reference station, taking into account the set interval of trains arrival and the port stations operation on the first day of planning

A comparative analysis of the simulation results for the two optimization scenarios has shown that it is possible to find the intensity in arrival of train traffic flows due to the higher punctuality of trains movement on the railway corridors, which allows reducing the fleet of locomotives by 5.2% per day from the scenario of actual operating conditions. Non-productive car detention on the tracks of the marshalling yards and port stations due to inconsistencies in the operation of the railway corridors and the port can be reduced up to 30% of the existing.

The obtained result proved the efficiency of finding a rational option for determining the motion intensity of specific train traffic flows on railway transport corridors with account for balance of expenses on traction resources and cargo owners. An expert analysis of the results of the simulation confirmed the adequacy of the solution. In order to take into account the reliability in the implementation of the proposed technology for the passage of cargo traffic flow under the individual conditions of movement on the railway corridors, solving the optimization mathematical model is proposed to perform, with regard to compliance with the level of reliable probability greater than = 0.95. To check the stability of the algorithm and to avoid its falling into the "trap of local optimums," the launch of the optimization algorithm was performed several times and with an acceptable convergence rate it was found 700 iterations.

5. Conclusions

The proposed mathematical model and the accepted method of its optimization allow us, in the conditions of risks, to find the interval between trailing trains in the railway lines taking into account the limited resources of the traction rolling stock, the capacity of the stations and freight fronts at the cargo destination point. The results obtained in this study differ from the existing ones by possibility of finding a balance between the expenses for movement of train traffic flows from different railway lines to their terminal reference station and the expenses of a consignee, subject to the forming the logistics chain in cargo transportation. Further research might also take into account the enterprise operation technology of the consignor and the stations for cars formation into trains at the beginning of the railway corridor. However, this does not reduce the significance of the results obtained. The technology of several corridors interaction, the reference marshalling yard and some port stations with loading/unloading terminals in the ports is more complicated, and the rhythm of sending the freight trains from the starting station of the railway corridor can be adapted according to the found interval.

The simulation results prove the effectiveness of the proposed approach, which allows to increase the adequacy of the planning process with regard to real conditions of transportation technology implementation. The found interval between the trailing trains on the railway transport corridors is the basis for detailed development of the train schedule, which is more adapted to the actual operating conditions of the railway network and the needs of the consignees.

References

1. Aleksandrov, A.E. and Yakushev, N.V. (2006) Stokhasticheskaya postanovka dinamicheskoy transportnoy zadachi s zaderzhkami s uchetom sluchaynogo razbrosa vremeni dostavki i vremeni potrebleniya. *Upravlenie bolshimi sistemami* [Stochastic statement of the dynamic transport problem with delays taking into account the random distribution of delivery time and consumption time]. *Large-Scale Systems Control: Procedeengs*, 12-13, pp. 5-14.
2. Badetskiy, A.P. (2013) Metod adaptatsii plana formirovaniya poezdov k sutochnoy neravnomernosti vagonopotokov [Method of adapting the plan for the formation of trains to the daily unevenness of car traffic]. *Phd Thesis*. Sankt-Peterburg.
3. Bektas, T. and Crainic, T.G. (2007) A Brief Overview of Intermodal Transportation, CIRRELT, In, Taylor, G. Don (ed.) *Logistics Engineering Handbook.* Boca Raton. CRC Press.
4. Bostel, N. and Dejax, P. (1998) Models and Algorithms for Container Allocation Problems on Trains in a Rapid Transshipment Shunting Yard. *Transportation Science*, 32(4), pp.370-379, 1998. Doi: 10.1287/trsc.32.4.370
5. Butko, T., Prokhorchenko, A. and Muzykin, M. (2016) An improved method of determining the schemes of locomotive circulation with regard to the technological peculiarities of railcar traffic. *Eastern-European Journal of Enterprise Technologies*, 5/3 (83), pp. 47-55. Doi:10.15587/1729-4061.2016.80471
6. Caprara, A., Malaguti, E. and Toth, P. (2011) A Freight Service Design Problem for a Railway Corridor. *Transportation Science*, 45(2), pp. 147-162. Doi:10.1287/trsc.1100.0348
7. Caris, A., Macharis, C. and Janssens, G.K. (2008). Planning Problems in Intermodal Freight Transport: Accomplishments and Prospects. *Transportation Planning and Technology*, 31(3), pp. 277-302. Doi: 10.1080/03081060802086397
8. Chen, C.-C., (F.) and Schonfeld, P. (2012) A Hybrid Heuristic Technique for Optimizing Intermodal Logistics Timed Transfer Systems. Procedia - Social and Behavioural Sciences, 48, pp. 2566-2576. Doi:10.1016/j.sbspro.2012.06.1227
9. Crainic, T.G. and Kim, K.H. (2006) Intermodal transportation. *Transportation*, 14, pp. 467-537.
10. Ferreira, L. (1997). Planning Australian freight rail operations: An overview. *Transportation Research Part A: Policy and Practice*, 31(4), pp. 335-348. Doi:10.1016/s0965-8564(96)00026-2
11. Herrera, F., Lozano, M. and Verdegay, J.L. (1998) Tackling Real-Coded Genetic Algorithms: Operators and Tools for Behavioural Analysis. *Artificial Intelligence Review*, 12(4), pp. 265-319. Doi: 10.1023/a:1006504901164
12. Hruntov, P.S., Diakov, Yu.V. and Makarochkyn, A.M. (1994) Upravlenie ekspluatatsionnoi rabotoi i kachestvom perevozok na zheleznodorozhnom transporte [Management of operational work and quality of traffic on the railway transport]. *Textbook*. Moscow: Transport.
13. Kasalica, S., Mandić, D. and Vukadinović, V. (2013) Locomotive Assignment Optimization Including Train Delays. *PROMET – Traffic&Transportation*, 25(5), pp. 1-10. Doi:10.7307/ptt.v25i5.1402
14. Macharis, C. and Bontekoning, Y.M. (2004) Opportunities for OR in intermodal freight transport research: A review. *European Journal of Operational Research*, 153(2), pp. 400-416. Doi:10.1016/s0377-2217(03)00161-9
15. Nahapetyan, A., Ahuja, K.R, Sargut, Z.F., Andy, J., Somani K. (2007) A Simulation/Optimization Framework for Locomotive Planning. *7th Workshop on Algorithmic Methods and Models for Optimization of Railways (ATMOS'07)*, pp. 259-276. Doi:10.4230/OASIcs.ATMOS.2007.1182
16. Nekrashevich, V.I. and Kudryashev, S.A. (2005) Metodika otsenki vliyaniya pokazateley ispolzovaniya lokomotivnogo parka po dorogam na ikh velichinu po seti v tselom [Methodology of the impact estimation of indicators of the locomotive fleet usage on the roads on their size on the network as a whole]. *Vestnik of the Railway Research Institute*, 6, pp. 15-20.
17. Pedersen, M.B. and Crainic, T.G. (2007) Optimization of Intermodal Freight Service Schedules on Train Canals. Publication, Montréal: Centre for Research on Transportation.

18. Powell, W.B., Bouzaiene-Ayari, B., Cheng, C., Fiorillo, R., Das, S. and Lawrence, C. (2012) Strategic Tactical and Real-Time Planning of Locomotives at Norfolk Southern Using Approximate Dynamic Programming. *Conference paper: Joint Rail Conference*. 10 p. Doi:10.1115/jrc2012-74187
19. Proschan, M.A. and Shaw, P.A. (2016) *Essentials of Probability Theory for Statisticians*. 1st Edition. Chapman and Hall/CRC Published.
20. Quaglietta, E., Corman, F. and Goverde, R.M.P. (2013). Stability analysis of railway dispatching plans in a stochastic and dynamic environment. *Journal of Rail Transport Planning & Management*, 3(4), pp. 137-149. Doi:10.1016/j.jrptm.2013.10.009
21. Sivilevičius, H. (2011) Modelling the interaction of transport system elements. *Transport*, 26(1), pp. 20-34. Doi: 10.3846/16484142.2011.560366
22. Su, R., Zhou, L. and Tang, J. (2015) Locomotive Schedule Optimization for Da-qin Heavy Haul Railway. *Mathematical Problems in Engineering*, 2015, pp. 1-14. Doi:10.1155/2015/607376
23. Sveshnikov, A.A. (1968) *Problems in Probability Theory, Mathematical Statistics and Theory of Random Functions*. Dover Publications; Reprint edition.
24. Talebian, A. and Zou, B. (2014) Train Planning on a Single Track Shared-Use Passenger and Freight Corridor With Demand Considerations. *Conference paper: Joint Rail Conference*, 10 p. DOI: 10.1115/JRC2014-3732.
25. Zhao, Y., Liu, R., Zhang, X. and Whiteing, A. (2018) A chance-constrained stochastic approach to intermodal container routing problems. PLoS ONE 13(2): e0192275. Doi:10.1371/journal.pone.0192275
26. Zhu, E., Crainic, T. G. and Gendreau M. (2014). Scheduled Service Network Design for Freight Rail Transportation. *Operations Research*, 62(2), Doi:10.1287/opre.2013.1254