This paper has investigated the technology of forwarding local wagons at railroad technical stations and established the need to improve it given the extra downtime of local wagons. The main issue relates to the considerable combinatorial complexity of the tasks of operational planning. Another problem is that as part of the conventional approach, planning a station operation and planning a local operation at it is considered separately. Another planning issue is the lack of high-quality models for the preparation of initial data, in particular, data on the duration of technological operations, such as, for example, shunting operations involving local wagons forwarding. To resolve these issues, a new approach has been proposed, under which the tasks of operative planning of a technical station's operation and its subsystem of local operations are tackled simultaneously, based on a single model. To this end, a mathematical model of vector combinatoric optimization has been built, which uses the criteria of total operating costs and wagon-hours spent at a station when forwarding local wagon flows, in the form of separate objective functions. Within this model, a predictive model was constructed in the form of a fuzzy inference system. This model is designed to determine the duration of shunting half-runs when executing the spotting/picking operations for delivering local wagons to enterprises' goods sheds. The model provides for the accuracy level that would suffice at planning, in contrast to classical methods. A procedure has been devised for optimizing the planning model, which employs the modern genetic algorithm of vector optimization NSGA-III. This procedure is implemented in the form of software that makes it possible to build a rational operative plan for the operation of a technical station, including a subsystem of local operations, in graphic form, thereby reducing the operating costs by 5 % and the duration of maintenance of a local wagon by 8 %. The resulting effect could reduce the turnover time of a freight car in general on the railroad network, speed up the delivery of goods, and reduce the cost of transportation

Keywords: optimization of local operations, technical station, railroad connecting lines, shunting half-run, combinatorial vector optimization

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CONSTRUCTING A MODEL FOR THE AUTOMATED OPERATIVE PLANNING OF LOCAL OPERATIONS AT RAILROAD TECHNICAL STATIONS

Artem Prokopov
Postgraduate Student*
Viktor Prokhorov
PhD, Associate Professor**
Tetiana Kalashnikova
PhD, Associate Professor**
Tetiana Golovko
PhD, Associate Professor**
Hanna Bohomazova
Corresponding author
PhD, Associate Professor*
E-mail: annabogomazova1234@gmail.com
*Department of Cargo and Commercial Work Management***
Department of Operational Work Management*
***Ukrainian State University of Railway Transport
Feierbakha sq., 7, Kharkiv, Ukraine, 61050

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1. Introduction

Under modern conditions, the task to accelerate the turnover of freight cars becomes increasingly important. The reason for this is that more industrial enterprises, in order to optimize their performance, abandon large warehouses and build production – transport – logistics chains to maximize the rate of flows of raw materials and finished products. According to statistics, the greatest share in the duration of freight car turnover belongs to processes taking place at the beginning and end of a rail run. It is during these periods that non-production downtime occurs while waiting for cargo operations at loading and unloading points and when awaiting operations at technical stations (freight, marshaling, district), as well as in the process of assembling/disassembling individual railcars in a train. The totality of car handling operations in the initial and final stages of transportation is termed local operations. Local operations on railroad transport start and finalize the transportation process, combines main and industrial vehicles, determines the modes of interaction between railroads and other modes of transport. Local operations account for a significant part in the train-related, shunting, and marshaling work, affects the qualitative and quantitative indicators of rolling stock utilization: freight cars, train and shunting locomotives. Local operations also exert a direct impact on the throughput of railroad lines, as well as the throughput and processing capacity of technical stations. Local operations involve the work performed at technical stations with railcars and cargoes arriving for unloading, loading, reloading, reweighing, marshaling of goods, for disinfection, or repair. Thus, operations with local cars are closely intertwined with all other operations at stations and often have common performers, such as shunting locomotives, teams of inspectors, etc. Given the deep integration between local operations and the work of a technical station, its optimization is impossible without optimizing the operation of the entire station. Therefore, optimizing local operations is a problem of a high degree of complexity both in terms of formalization and deriving specific solutions that could be applied in practice.

Thus, the task of operative planning of local operations is a relevant challenge of present-day railroad transportation and is a key issue in resolving its most important problems. Such tasks include ensuring the delivery of goods on time, improving the utilization factor of freight cars, and reducing the operating costs for executing local and shunting operations at technical stations.

2. Literature review and problem statement

Scientific studies aimed at optimizing the methods of operative planning of the work of technical stations and technologies for servicing enterprises' railroad connecting lines are directly related to the issue of non-production downtime of local railcars. Thus, paper [1] considers some tasks related to the tactical and operative planning of managing a fleet of rolling stock vehicles. The emphasis is on the application of combinatorial optimization methods for solving such problems, however, the approaches given in the cited paper are very general. Study [2] addresses issues related to optimizing the delivery of goods over the last mile. The focus is on reducing energy costs; however, mostly classical approaches are proposed for solving the problems. In [3], attention is paid to the planning of rolling stock under the conditions of operation execution at railroad infrastructure sites. The proposed mathematical models correctly formalize processes with fuzzy duration terms, but some other important factors, such as track development topology, are not paid appropriate attention to. Paper [4] suggested an original logistics model for the delivery of local cargoes using CargoSprinter-type trains; however, this model only considers cargoes transported in containers. In [5], a model is proposed that simultaneously optimizes the plan for the formation of trains and their routes. That model has a direct impact on the downtime of local cars but the cited study resolves the issue of tactical, rather than operational, planning of local stations operations. A model of mixed-integer programming is proposed in [6] to solve the task of detailed planning of local operations. However, the cited work considers only the case of intermodal terminals. Study [7] considers the problem of optimizing the planning of a marshaling station operation based on a model that represents the sequence of operations using a flow network; however, no special attention is paid to the task of optimizing local operations. In [8], a comprehensive model is suggested for the operative-tactical planning of assembling/disassembling individual railcars in a train at a marshaling station using integer programming. However, the focus of optimization is on minimizing the number and time of station tracks utilization by their dynamic specialization. Paper [9] addresses the detailed modeling of technological processes at a marshaling station but the problem of optimizing its operation was not paid attention to. Article [10] tackles the issue of predicting the time of departure of freight trains from a technical station but no mechanisms that influence the formation of trains in order to speed it up were proposed.

Thus, the task of optimizing the system of operative planning of technical stations operation, as well as the issue of traveling the «last mile», which lies on the way of transportation of local goods between main railroad companies and industrial enterprises, are relevant. The main disadvantage of existing approaches is that these problems are solved separately. An option for overcoming appropriate difficulties may be the application of modern approaches to the construction of integrated management models using digital technologies. All this gives reason to assert that it is advisable to conduct a study into the construction of an integrated model of operative planning of the local operations of railroad technical stations under the conditions of digitalization.

3. The aim and objectives of the study

The purpose of this work is to build a model for the operational management of a technical station and a subsystem of local operations as its part. Such a model should be aimed at reducing the technological costs of processing local cars and minimizing their non-production downtime by introducing logistical principles based on the use of digital technologies.

To accomplish the aim, the following tasks have been set:

– to build a model of forecasting the duration of shunting half-runs when executing the operations of spotting/picking local cars to deliver them to the goods sheds of enterprises' railroad connecting lines with the accuracy sufficient for the operative planning of station operation;

– to construct a model of the operational management of a technical station, which would make it possible to optimize the subsystem of local operations in order to minimize the downtime of local railcars. The proposed optimization mathematical model should be implemented in the form of a computer procedure using which could produce a rational operative plan for a technical station operation.

4. The study materials and methods

This study employed data from time-lapse field observations of the duration of shunting half-runs at a marshaling station and when moving the shunting trains between the station and enterprises' connecting lines. The sample size exceeded 1,000 units. Each unit is a tuple whose first attribute contains a value for the duration of a half-run. Other attributes contain data that describe the conditions under which this duration value was acquired, such as the length of the route, the length and weight of a shunting train, etc. A mathematical apparatus of fuzzy logic was used in the process of building a model for predicting the duration of shunting half-runs during operations. The application of this apparatus has made it possible to construct a flexible universal predictive model in the form of a fuzzy inference system. A given model allows us to configure both the system of fuzzy rules and the terms of linguistic variables on actual data using multi-agent methods.

No methods of competing criteria synthesis or convolution were involved while building an optimization model of the operative planning of local operations at a technical station. Therefore, a vector optimization model was constructed. When devising an optimization procedure, the Pareto-based optimality principle [11] was used. Pareto-based optimal solutions essentially imply those solutions in which none of the criteria could be improved without compromising at least one other criterion. Thus, in general, there is no solution that would be optimal in terms of all criteria but there is instead a whole set of Pareto-based optimal solutions. A given model in the case of a problem with large dimensionality could have many alternative solutions; the search for the Pareto set, in this case, is a computationally complex process. In order to accelerate it, a modern mathematical apparatus was used, such as a special genetic algorithm for vector optimization, the type of NSGA-III [12]. This algorithm performance rate is explained, in particular, by the fact that the algorithm makes it possible to significantly narrow down the set of Pareto-optimal solutions, providing, at the same time, for the level of diversity necessary from a practical point of view. The next step after acquiring a given set is to separate a single final solution. There are different methods for carrying out this operation. In this case, the main criterion for choosing a method is the ability to manage the weights of criteria to ensure the required degree of flexibility in planning. Given the relative simplicity of implementation, the weighted metrics method (WMM) [13] was applied. The method essentially implies the minimization of Chebyshev's metric between the vector of solutions in the criterion space and the ideal vector of criteria.

5. Results of studying the process of operative planning of local operations at a technical station and its formalization

5. 1. Investigating approaches to determining the duration of shunting half-runs at a technical station and their formalization

Railroad connecting lines are tracks intended for rendering transport services to one or more enterprises that are connected to the common network of railroads by continuous rail route and belong to a railroad operator or an enterprise. Servicing enterprises involves sending railcars for loading or unloading and taking loaded or empty cars from goods sheds, which are connected by road tracks to a railroad station. The classic servicing technique typically takes the form shown in Fig. 1, *a*. The head of shunting operations would rather choose simple schemes for the spotting/picking of wagons, even realizing that those solutions are far from optimal ones. That happens because, in order to make more optimal decisions, it is necessary to calculate them by sorting out many possible options for an operative work plan. And this is a complex combinatorial problem whose solution requires that the shunting dispatcher should build a detailed schedule of all relevant shunting movements. It is also necessary to determine the number of cars in each batch, which depends on the availability of these cars at a certain point in time, which, in turn, depends on the order of assembling/disassembling individual railcars in a train, as well as many other factors. One of the most important factors, which is now paid attention to only on a residual basis, is the need to minimize the downtime of local cars. It is also necessary to take into consideration the time windows of goods sheds operation, to coordinate the work of shunting locomotives by switching them from local operations and other technological operations at a station. In addition, areas of marshaling and large technical stations typically have extensive networks of industrial railroad transport. Underlying these networks are the enterprises' railroad connecting lines, which are interconnected without utilizing tracks at a station. The use of these connecting lines could significantly reduce the total duration of shunting movements, but only if one plans the integrated operations of railcar spotting/picking, as shown in Fig. 1, *b*. Thus, it is impossible to effectively solve the problem of minimizing the downtime of local cars without the use of modern computing tools and digitalization technologies. One needs to build an appropriate base to switch to the logistical principles of managing local operations, which may take the form, for example, shown in Fig. 1, *b*. The basis of such a base should include complex predictive and optimization mathematical models that would be connected through data integration, which is achievable by the introduction of modern technologies of digitalization.

The first step to build such a base that would become the basis for the digital transformation of station process management systems and a subsystem of local operations is to construct predictive models. These models should be able to predict the duration of technological operations at a station with sufficient accuracy.

Modern advances in the field of automation and digitalization of technological processes to handle freight trains are already able to significantly increase productivity and safety at technical stations. One of these technological advancements is a modern version of the automated system for an integrated unit for receiving and diagnosing rolling stock (URDR). This system is able not only to identify the rolling stock and recognize the number plates of railcars but also actually perform routine operations on the technical and commercial inspection of trains using technical devices and complex algorithms. Information from this system is instantly transmitted through communication channels to the central station control system. Automation of individual processes, while making it possible to reduce the time of operations and improve their quality, does not yet solve the main task of the digital transformation of the control system for a technical station and the process of transportation in general. This task is to centralize and automate the processes of transport process management on the railroad. One of the most important aspects in managing a technical station is the process of operative planning of its operations. The process of operative planning of the operation of such a complex system as a technical station involves making up a detailed schedule of operations. This schedule connects a set of operations in space and time, which includes all technological operations at a station, to a set of their performers. Technical devices such as park tracks, hill mechanisms, shunting locomotives, etc. act as performers. Therefore, the basis of this process should be an optimization mathematical model, which is built using the principles of decomposition theory [14]. The initial data for such a model are also of great importance because the quality of the received plan directly depends on their accuracy. In this sense, the automation of individual processes and, in particular, the introduction of systems such as URDR system play a significant positive role because these systems, while minimizing the human factor, make it possible to more accurately predict the duration of individual technological operations.

Some station operations, such as fixing trains with wheel chocks, or testing the auto-brakes by a locomotive crew, are standard and typically have a small value of variance in the value of their duration. In addition, they are not long-term, so predicting the time of their execution with enough accuracy to plan the operation of a station is not particularly difficult. Such standard operations include some routine movements of shunting locomotives, such as the arrival of a hill locomotive in the receiving park.

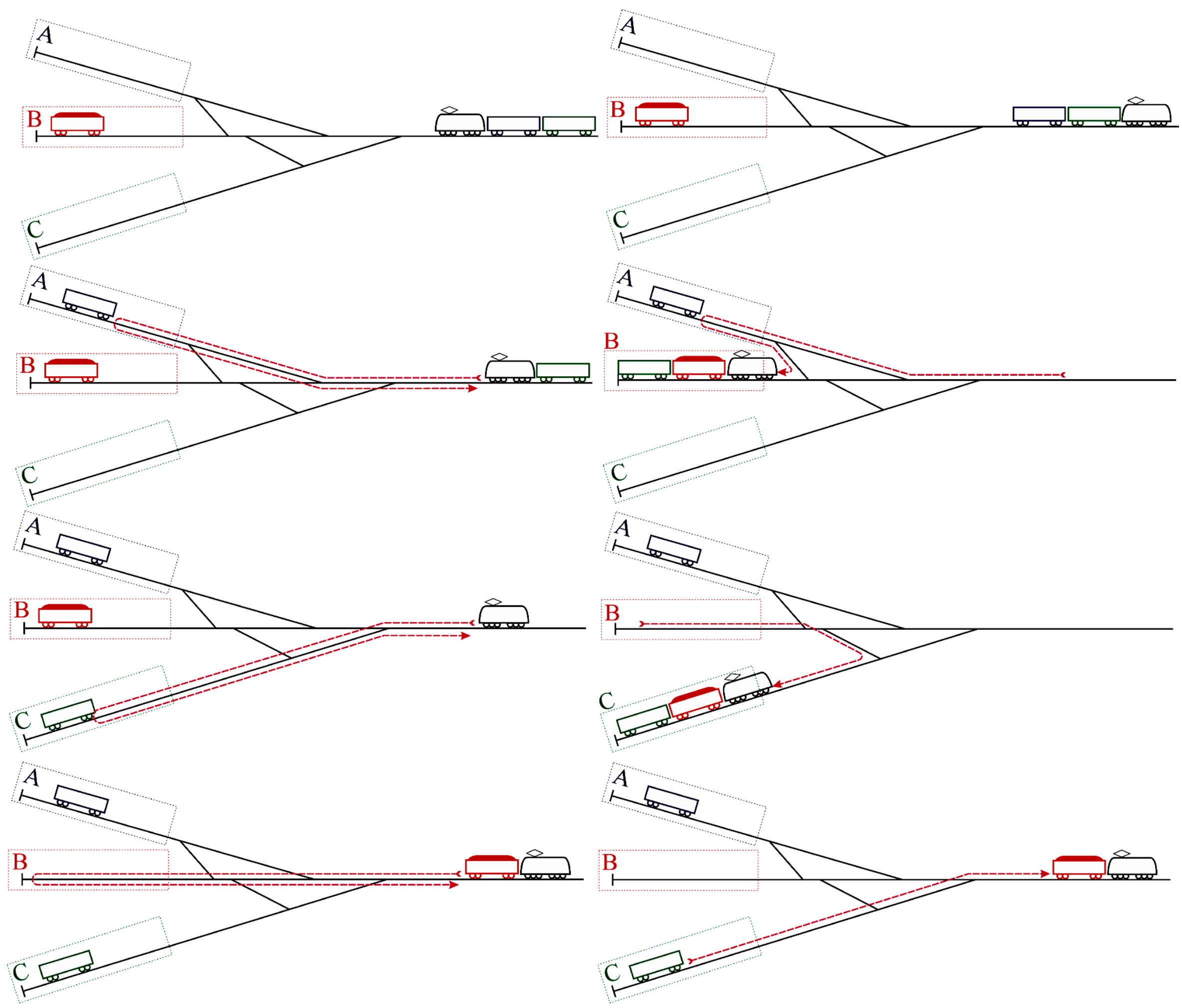

Fig. 1. Schemes that execute the operations of spotting/picking railcars for enterprises' goods sheds:
a — conventional; *b* — logistical

Therefore, the process of planning the operation of a station in order to predict the time of various operations, including shunting movements, often employs those models that assume that the duration of an operation is distributed according to the normal law [15].

However, predicting the duration of certain operations, such as shunting half-runs when spotting/picking local cars, is still a difficult task.

The reason for the lack of significant attention to them is that the main interest of researchers of station processes is aimed at solving the problems related to planning the subsystem of assembling/disassembling individual railcars in a train. In the American tradition, the marshaling yard in general is a separate system in which assembling/disassembling individual railcars in a train is the only function it performs.

Existing procedures to forecast the duration of shunting half-runs are few and are mostly based on a linear model [16]. Some of them try to improve the accuracy of calculations using statistical data and the construction of models of multifactorial regression [17], which also lead to a multivariate linear model.

The essence of the linear model is that the duration of a shunting half-run could be determined from the following formula [18]:

$$t = a + b \cdot m, \tag{1}$$

where a and b are the coefficients that depend on the distance of movement, the coefficient b also depends on the state of auto-brakes (on or off); m is the number of cars in a train.

When applying this linear dependence to predict the duration of shunting movements over short distances within a station, one could obtain the level of accuracy close to satisfactory. However, this is possible only if the coefficients a and b are refined by timing full-scale observations that make it possible to take into consideration the local conditions of a station.

However, the development of automation systems for station management leads to the need to integrate the processes of operative planning of all station subsystems, their temporal coordination and synchronization. That encourages the construction of more accurate and adequate models for predicting the duration of shunting half-runs when servicing enterprises' railroad connecting lines because railcar spotting/picking operations are one of the key links linking the subsystem of assembling/disassembling individual cars in a train to the subsystem of local operations at a station.

The duration of shunting half-runs performed during the operations of assembling/disassembling individual cars in a train for enterprises' goods sheds depends in practice on many factors. Our research was carried out using data from chronometric observations at a marshaling station, which included 43 connecting lines. Based on the study results, it was found that the average absolute percentage error of the forecast [19], derived on the basis of Frolov formula, was MAPE=18.1 %. Such accuracy in estimating the duration of technological operations is unsatisfactory for their application during the process of operative planning of a station's operation. In order to improve the accuracy of estimating the duration of shunting half-runs, a predictive model in the form of a fuzzy inference system (FIS) of the Mamdani type [20] was built on the basis of observation data. The fuzzy inference system is a fuzzy production system that stores knowledge in the form of a database of fuzzy rules. The fuzzy inference system as a mathematical function can be represented as follows:

$$\Psi(x)=\bigcup_{k=1}^{\#R}\left(w_k \odot\left(\bigotimes_{i=1}^{\#x}\left(\mu_{i,a_{k,i}}^{input}(x_i)\right),\mu_{c_k}^{output}\right)\right), \qquad (2)$$

where x is the vector of implicit input variables; $\#R$ is the power of a set of rules, which comprises a fuzzy knowledge base; $\#x$ is the power of the set of elements of the vector of input variables; w_k is the weight of the k-th rule; $\mu_{i,a_{k,i}}^{input}(x_i)$ is the degree of membership of the input variable x_i to the fuzzy set defined by the term of the i-th input linguistic variable, which corresponds to the i-th antecedent of the k-th fuzzy rule $a_{k,i}$; $\mu_{c_k}^{output}$ is the degree of membership of the output variable, which corresponds to the consequent of the k-th fuzzy rule c_k; $\otimes$ – the operation of t-norm; $\odot$ – the operation of Mamdani implication; $\cup$ – aggregation operation.

Fig. 2 shows the membership functions of the term sets of 6 input and 1 output fuzzy variable models.

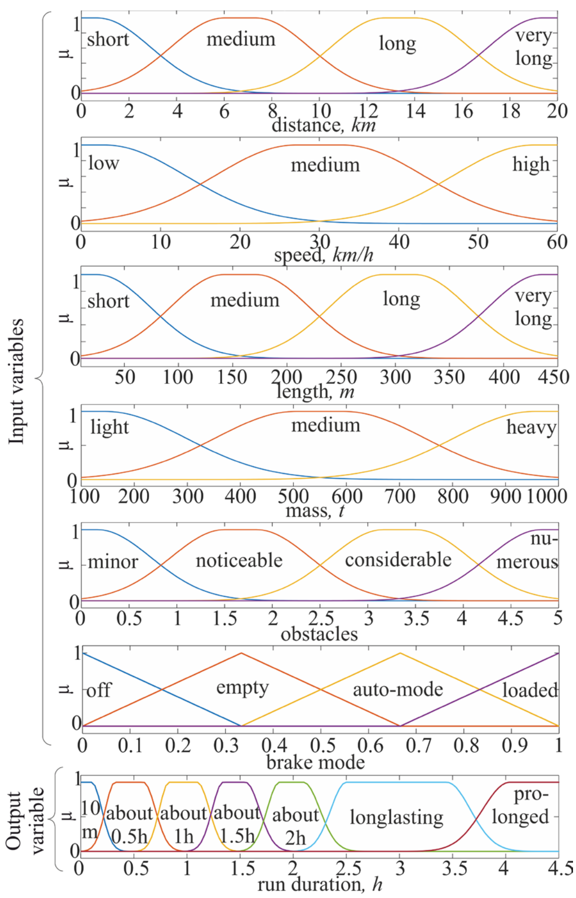

Fig. 2. Term sets of the input and output linguistic variables of FIS-model for forecasting the duration of shunting movements

Thus, the model takes into consideration the dependence of the duration of a shunting half-run on route distance, the allowable speed, length, and weight of a train, the number of obstacles along its run, and the mode of operation of auto brakes. At the same time, Frolov formula takes into consideration the maximum speed of movement, which is determined only by the mode of operation of auto brakes. Judging by the tabular values for coefficients a and b in Frolov formula, the speeds of 60 km/h and 40 km/h for modes with auto brakes turned on and off, respectively, were taken into consideration. However, the actual allowable speeds of shunting trains can also take values that are very different from those specified above. In addition to auto brakes, other factors could significantly affect this, such as the location of a shunting locomotive in the train. A significant impact is also exerted by the existence of speed restrictions due to the repair work or track condition, whether the next section of the route is free, the type of cargo transported, etc. For example, cars loaded with some types of dangerous goods cannot be moved as part of a shunting train at a speed exceeding 5 km/h. Obstacles along the run of a shunting train, such as crossing points with highways, also prolong the route duration by the time it takes to braking and acceleration. This time, respectively, also depends on the inertia and mass of the train. In addition, the closing time of the crossing, which is essentially a random value, also affects it. The main modes of auto brake operation are «off» and «auto-mode». However, the model also provides an opportunity to differentiate the cases of movement of trains with their brakes on, when the mode switches on cars are in the «empty» or «loaded» position. This model was implemented in MATLAB. The core of the model contains 62 fuzzy rules that were generated automatically based on statistical sample data with more than 1,000 observations. Based on this sample, we configured the membership functions of term sets of linguistic variables of the model using the algorithm of ant colonies. The average absolute percentage error of the forecast, which was obtained on the basis of the model built, was MAPE=5.9 %. This accuracy of the forecast is satisfactory for using a given model in the preparation of initial data during the planning procedure of local operations at a technical station.

5. 2. Studying the process of managing the subsystem of local operations in the context of operative planning at a technical station

At many technical stations, the number of goods sheds is much larger than the number of shunting locomotives servicing them. Most of them are located along the connecting lines of industrial enterprises. Large technical stations, which primarily include marshaling stations, typically include at least several dozen connecting lines, a significant number of which could be located at a significant distance from the station. And even when the goods sheds are in close proximity to the station or within its territory, the length of such stations could reach 20 km or more. Under such conditions, the heads of shunting operations at technical stations always face a dilemma when it is necessary to service several goods sheds at the same time. So, an issue arose related to the order of spotting/picking local cars. However, under the current conditions of digital transformation of transport control systems, it is necessary to move from local tasks to their integration and comprehensive solution. That is, it is necessary to move from the tasks of determining the order of spotting/picking shunting locomotives to the task of servicing the goods sheds of industrial enterprises in the context of optimizing the process of operative planning of technical stations. Thus, the chosen criterion for such optimization, first of all, is the operating costs arising in the implementation of the technological process of handling railcar flows at a station. The objective function corresponding to this criterion can be represented in the following form:

$$
\begin{aligned}
&f_1\left(m, M^{dep}, t^{dep}\right)= \\
&= c_{r\cdot h}\left(\begin{array}{l}
\sum\limits_{i=1}^{\# N^{arr}}\left(t^{pl}-t_i^{acc}\right) M_i^{arr}+ \\
+\sum\limits_{i=1}^{q} \sum\limits_{j=2}^{\# p_i-1}\left(t^{pl}-t_i^{pick}\right) m_{ij}- \\
-\sum\limits_{i=1}^{\# N^{dep}}\left(t^{pl}-t_i^{dep}\right) M_i^{dep}
\end{array}\right)+ \\
&+c_{t\cdot h} \sum_{i=1}^{\# N^{arr}}\left(t_i^{acc}-t_i^{A}\right)+ \\
&c_{l\cdot h} \sum_{i=1}^{q} \sum_{j=2}^{\# p_i-1}\left(\begin{array}{l}
\Psi\left(\begin{array}{l}
l_{j-1,j,i}, V_{j-1,j,i}, \\
\sum\limits_{v=2}^{j} \sum\limits_{w=v-1}^{\# p_i} m_{w,v,i} \lambda_{w,v,i}, \\
\sum\limits_{v=2}^{j} \sum\limits_{w=v-1}^{\# p_i} m_{w,v,i} \mu_{w,v,i}, \\
o_{j-1,j,i}, b_i
\end{array}\right)+ \\
+\tau_{i,j}^{\mathrm{dis}} Sgn\left(m_{1,j,i}\right)+ \\
+\tau_{i,j}^{\mathrm{ass}} Sgn\left(m_{j,1,i}\right)+ \\
+\theta\left(t_{j,i}^{gs}-t_{j,i}^{arriv}\right)\left|t_{j,i}^{gs}-t_{j,i}^{pick}\right|
\end{array}\right) \rightarrow \min,
\end{aligned}
\qquad (3)
$$

where m is the three-dimensional array that contains the value of the number of cars during the operations of spotting/picking cars for the goods sheds of connecting lines; M^{dep} is the vector containing information about the number of cars in the formed trains departing from a station; t^{dep} is the vector containing information about the moments of departure of the formed trains from a station; $c_{r\cdot h}$ is the cost of railcar hour; $c_{t\cdot h}$ is the cost of a train hour; $c_{l\cdot h}$ is the cost of a locomotive hour of the shunting operation; t^{pl} is planning time horizon; t_i^{acc} – the time of accepting the i-th train to a station; M_i^{arr} – the number of cars in the i-th train arriving at a station; q – the number of combined runs of spotting/picking the cars for goods sheds during a planned period; $\#p_i$ – the power of a set of stops (goods sheds) of the i-th spotting/picking run; t_i^{pick} – the moment of completing the i-th spotting/picking run, which corresponds to the picking time of the i-th batch of local cars from enterprises' goods sheds to a station; m_{ij} – the number of local cars picked from the j-th point during the i-th spotting/picking run; $\#N^{arr}$ – the power of the set of trains arrived at a station; $\# N^{dep}$ – the power of the set of formed and dispatched trains; M_i^{dep} – the number of cars in the i-th train dispatched from a station; t_i^{c} – the time of arrival of the i-th train to the entrance traffic light of a station; $\Psi(...)$ – a fuzzy function that returns the time of the duration of a shunting half-run during the operation of spotting/picking; $l_{j-1,j,i}$ – the length of the section connecting the j-th–1 and the j-th cargo areas of the i-th shunting run; $V_{j-1,j,i}$ – the speed that allows a shunting train to move between the j-th–1 and the j-th points of the i-th run; $m_{w,v,i}$ – the number of cars as part of a shunting train, forwarded from point w to point v, transported during the i-th shunting run; $\lambda_{w,v,i}$ – the length of one car as part of a group of cars forwarded from point w to point v, transported during the i-th shunting run; $\mu_{w,v,i}$ – the weight of one car as part of a group of cars forwarded from point w to point v, transported during the i-th shunting run; $o_{j-1,j,i}$ – the number of obstacles along the way between the j-th–1 and the j-th points of a run; b_i – the operation mode of the braking system of a shunting train during the i-th run; $\tau_{i,j}^{dis}$, $\tau_{i,j}^{ass}$ – the duration of disassembling/assembling local cars, respectively, at the j-th point of the i-th shunting run; $Sgn(...)$ – the sign function; $m_{1,j,i}$ – the number of cars to be disassembled at the j-th point during the i-th shunting run; $\theta(...)$ – the Heaviside function; $t_{j,i}^{arriv}$, $t_{j,i}^{gs}$ – the moments of arrival time of a shunting train to the j-th point and the start of its goods shed operation during the i-th run.

The first term reflects the costs associated with the car hours that cars, including transit ones, spend at a station. The first and second components in the first term simulate the so-called arrival curve. This curve reflects the dynamics of the number of cars arriving at a station as part of trains and from connecting lines during the planned period. The third component in the first brackets simulates the departure curve, which reflects the dynamics of the number of cars that left the station as part of trains. Thus, the total car hours spent when all cars are at a station during the planned period could be calculated as the plane of the geometric shape between the arrival and departure curves. The second term corresponds to the costs associated with train hours of waiting, which arise when there is a delay in issuing a permit to train drivers to enter a station due to that the tracks in a receiving park are busy. The third term simulates the costs associated with the locomotive hours of shunting operations, which are spent on executing the operations of spotting/picking local cars for enterprises' goods sheds. Its components reflect the costs arising from the implementation of shunting half-runs, waiting for the operations of car disassembling/assembling, and waiting for the moments to start the operation of enterprises' goods sheds.

As research shows [21], a freight car is in motion for only 12 % of the time of the total duration of transportation. A large part of the time is spent in the starting and final stages of transportation, that is, at freight points and technical stations where the operations of assembling/disassembling individual railcars in a train are carried out. Thus, technical stations are a potential source of reserves for improving the productivity of a freight car, which could be implemented only through the development and implementation of effective technologies for operative planning of their operations.

Of course, a technical station, from an economic point of view, is a business entity and, therefore, the optimization of total current technological costs is an important component of its operational activities. However, when guided only by this criterion, it is impossible to qualitatively solve the task of improving the technology for handling local cars at a station. Moreover, taking into consideration only this criterion does not provide an opportunity to solve such systemic problems as the increase in the turnover time of a freight car on a railroad network due to the increased downtime of local cars. This, in turn, provokes the problems of short-earnings of railroad enterprises due to the shortage of rolling stock, late delivery of goods, and a decrease in the quality of transport services provided to customers of railroads. However, resolving these issues is the basis for gaining an economic effect, which, at the system level, could be much higher than local savings on shunting operations at technical stations. Consequently, the planning process must be given some flexibility and flexibility to ensure that local operation parameters could be influenced so that a quality set of alternatives to the operative plan is devised. To this end, the criterion of the average time that a local car spends at a station should be included in the model in the form of a separate objective function:

$$f_2\left(m, M^{dep}, t^{dep}\right) = \sum_{i=1}^{\#N^{arr}} \left(t^{pl} - t_i^{acc}\right)\gamma_i^{arr} M_i^{arr} + \\ + \sum_{i=1}^{q} \sum_{j=2}^{\#p_i - 1} \left(t^{pl} - t_i^{pick}\right) m_{ij} - \\ - \sum_{i=1}^{\#N^{dep}} \left(t^{pl} - t_i^{dep}\right)\gamma_i^{dep} M_i^{dep} \rightarrow \min, \quad (4)$$

where γ_i^{arr}, γ_i^{dep} is the share of local cars in the i-th train arriving at a station and departing from the station, respectively.

During optimization, it is necessary to take into consideration the restrictions imposed on the control variables of the model:

$$\begin{cases} m_{1,b,i} \le Q_b^{gs}, \quad \forall b,i \;\; b \in S_i, i = 1 \ldots q, \\ \sum_{i=1}^{q} m_{1,b,i} \le M_b^{pl}, \quad \forall b,i \;\; b \in S_i, \\ \sum_{j=1}^{a} m_{a,b,i} \le M_{a,b}^{\max}, \quad \forall a,b,i \;\; b \in S_i, a < b, i = 1 \ldots q, \end{cases} \quad (5)$$

where Q_b^{gs} is the maximum capacity of a goods shed on the railroad connecting line b, expressed in cars; S_i is the set of numbers of points along the route of the i-th shunting run; $m_{1,b,i}$ is the number of cars for dispatching from a station to the goods shed b during the i-th shunting run; M_b^{pl} is the need for cars declared by enterprise b for the current planned period (for example, 24 hours); $m_{a,b,i}$ is the number of cars forwarded from point a to point b to be moved during the i-th shunting run; $M_{a,b}^{\max}$ is the maximum number of cars that a shunting train can include, when moving along the railroad tracks between points a and b in accordance with current technical restrictions or local conditions.

The first restriction prevents the forwarding of cars to a goods shed in the quantity exceeding the goods shed's capacity. The second restriction prevents the forwarding of cars to enterprises' goods sheds in the quantity exceeding the volume of orders. The third restriction prevents the planning of such combined shunting runs during which conditions may be violated regarding the maximum length of a shunting train along at least one of the sections of the route.

A set of criteria for a given model can be represented as a vector, which consists of two elements. Each criterion is represented by a separate objective function. Thus, in this form, the task of making up an operative plan for the operation of a technical station is the vector optimization problem [22], which can be represented as follows:

$$\begin{cases} f_i\left(m, M^{dep}, t^{dep}\right) \rightarrow \min, \left(i = \overline{1,2}\right), \\ \left\{m, M^{dep}, t^{dep}\right\} \in \Omega, \end{cases} \quad (6)$$

where Ω is the region of valid solutions.

To optimize the model, it is advisable to use a specialized genetic algorithm, the type of NSGA-III. The application of a genetic algorithm requires the representation of a solution in the form of a special vector termed a chromosome. The scheme for coding the chromosome of the genetic algorithm to solve a given problem is shown in Fig. 3.

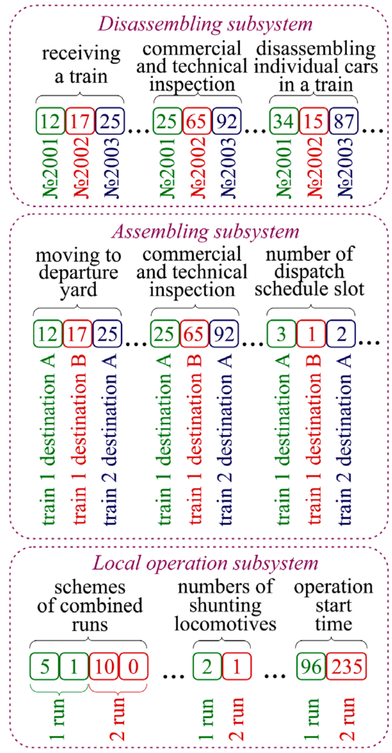

Fig. 3. The scheme of chromosome encoding by the genetic algorithm NSGA-III for solving the task of the operative planning of technical station operation

The chromosome consists of three sections, each containing genes representing variables that belong to the subsystems of disassembling, assembling, and local operations, respectively. The genes of the disassembling and assembling sections contain values representing the moments of operations' onset, expressed in minutes from the end of the preceding operation, which involved a given train. The assembling section subsystem also contains genes that determine the numbers of movement schedule threads that could be used to dispatch assembled trains from a station. The local operation section contains schemes of combined runs for spotting/picking local cars to enterprises' goods sheds. The scheme of each run is represented by two genes, the first is responsible for spotting the cars and the second – for picking the cars. Each of these genes represents a decimal notation of a binary number. Each bit of this binary number represents the number of a goods shed at an enterprise. Unity at the position of each bit means the inclusion of the corresponding operation with a given cargo area to a given run. Thus, the scheme (5;1) means that during this combined run the operations of forwarding to the first and third goods sheds are to be carried out and, at the same time, the operation of picking the cars from the first goods shed is to be carried out. In addition, the local operation section contains genes that determine which shunting locomotive is to perform the corresponding run. This section also contains genes that determine the start moments of runs, expressed in minutes from the onset of the planned period.

Based on the built model and the formed procedure for its optimization, we developed software in the MATLAB language. The software was used for simulation that produced the result shown in Fig. 4.

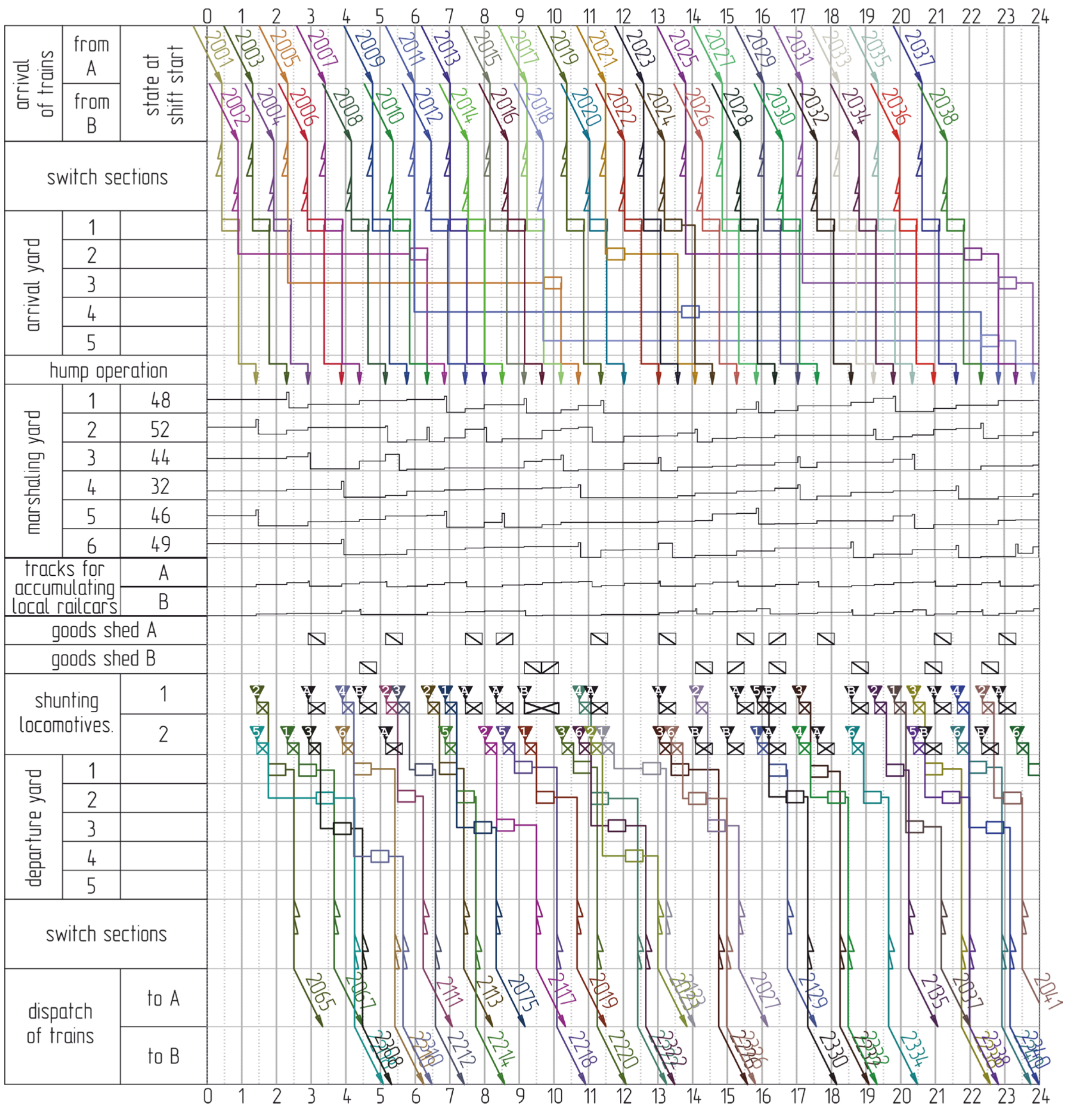

Fig. 4. Operative schedule for a technical station, which includes a subsystem of local operations, built as a result of model optimization

This plan chart shows that the process of accumulating the cars on the tracks of the marshaling yard is concave, which indicates its effectiveness. In the receiving yard, only those trains that do not include local cars or closing groups experience considerable downtime. All other trains are disassembled almost immediately after undergoing technical and commercial inspection operations. The process of servicing goods sheds is rhythmic and relatively frequent. This nature of the process leads to a certain increase in the volume of shunting operations but makes it possible to minimize the downtime of local cars on the dedicated tracks of the station and along the connecting lines of enterprises. The above schedule chart was compiled for a small technical station working with a load level close to maximal. Even under such conditions, the operating costs were partially reduced by an average of 5 % compared to classical management technique (Table 1). Although this decrease would be less than a percentage from the total operating costs, this is still a positive result.

At the same time, there was also a decrease in the total time that local cars spend at a station, by an average of 8 % (Table 1). In addition, a given station had only 2 connecting lines. Under the conditions of a larger station with a lower load factor and more connecting tracks, the second indicator could be significantly improved.

Table 1

Value of criteria derived from modeling

criterion	conventional technology	based on the optimization model	absolute difference	relative difference
partial operating cost, USD	16,345.76	15,588.95	–756.81	–4.63 %
the average duration of stay of a local car at a technical station, min.	927.3	856.1	–71.2	–7.68 %

6. Discussion of results of studying the process of managing the subsystem of local operations at a technical station

A significant success of our study is that it was possible to build a model of the functioning of such a complex railroad system as a technical station: formulas (3) to (6), Fig. 4. And this is the optimization model, not just simulation, in contrast to [9]. The model constructed effectively solves the task of speeding up the dispatching of cars, including local ones, from a station, rather than only predicts this moment, in contrast to [10]. That was possible due to the fact that the proposed approach was used to simultaneously optimize the operation of a station and local operations (Fig. 4), as well as the logistical approaches to the organization of combined shunting runs for servicing the goods sheds of industrial enterprises (Fig. 1, *b*). In addition, the built models, as well as the software developed on their basis, make it possible, in contrast to [7, 8], to, simultaneously with the processes of trains disassembling/assembling at a technical station, to effectively optimize the subsystem of local operations (Table 1). Another important factor is the use of a modern mathematical apparatus of genetic algorithms (Fig. 3), which, unlike [1–6], has allows us to simultaneously optimize the operation of a station according to all the required criteria. The application of a mathematical apparatus of fuzzy logic has made it possible to construct a high-precision predictive model (2), Fig. 3, to determine the duration of shunting operations. Employing this model as part of the optimization model (3) to (6) has allowed us to improve the reliability of the compiled operative plan (Fig. 3).

Thus, the proposed approaches and constructed models make it possible to reduce non-production downtime of local cars at a technical station and at enterprises' goods sheds (Table 1) and, at the same time, to optimize the operation of all functional subsystems of the station. At the same time, a given model, even under the conditions of finding a compromise between partially competing criteria, such as the operating costs of a station and the cost of car hours when handling local car flows, makes it possible to get improvements on both criteria (Table 1) compared to conventional management methods (Table 1, Fig. 1, *a*).

A certain limitation of this study is the fact that when using a genetic algorithm, it is impossible to warrant that the resulting solution would be absolutely optimal, but is only close to it.

The disadvantages of the current work include the fact that the decision-making process is, to some extent, hidden from the user. The proposed model does not use a mathematical apparatus that has clear semantics, such as the Petri networks. Instead, a mathematical apparatus of genetic algorithms is used; no unified theory of its functioning has been built yet.

Further advancement of the proposed approaches may include solving the task of automating the planning process of the entire unit, which has several marshaling stations that serve common car flows at once. However, resolving this issue will at least require considerable effort to organize the computational process.

7. Conclusions

1. We have proposed a model for predicting the duration of shunting half-runs when executing the operations of spotting/picking local cars for the goods sheds of industrial enterprises. In contrast to existing models that use only 3 factors, such as route length, the speed and number of cars, our model employs 6 factors. Thus, a given model makes it possible to additionally take into consideration the mass of a train, the existence of obstacles along its route, and the mode of operation of auto brakes. In addition, instead of the indirect value, such as the number of cars, the model directly uses the length of train, which additionally makes it possible to improve the accuracy of calculations. The error of the forecast obtained using a given model is on average 6 %, and is much lower than the error in conventional methods for calculating this value.

2. A model of operative management of a technical station has been built, which makes it possible, in the course of operative planning, to optimize the subsystem of local operations simultaneously with the optimization of the work of the entire technical station, using, in particular, a model for predicting the duration of shunting half-runs. The constructed mathematical model makes it possible to simultaneously take into consideration the total operating costs associated with handling trains and car flows, as well as and the car hours that local cars spend at a station, as optimization criteria. Thus, a given model represents the problem of vector combinatoric optimization. The procedure for optimizing this model was implemented in the form of software that employs modern mathematical apparatuses and algorithms, in particular, a special genetic algorithm for vector optimization, the type of NSGA-III. This software product was implemented in the MATLAB language. When using it, a rational variant of the operative plan for technical station operation was devised. This plan contains a detailed schedule of the operation of shunting locomotives in the implementation of operations for spotting/picking local cars for enterprises' goods sheds whose connecting lines are adjacent to the station. Minimizing the duration of non-production downtime of local cars and, as a result, reducing the total time of their stay at a station (Table 1) leads to a reduction in the turnover time of a freight car and the acceleration of the delivery time of goods.

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