https://doi.org/10.33271/nvngu/2024-1/147

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IMPROVEMENT OF THE METHOD OF TIME RATIONING FOR ASSEMBLING CAR GROUPS ON ONE TRACK

Purpose. To improve the method for standardizing the duration of the shunting operation of assembling cars on one track. This can be achieved as a result of solving the following research problems: development of a method for searching the optimal order of assembling cars on one track; distribution parameters estimation of the random value of the duration of shunting operation of assembling cars on one track based on calculation experiments.

Methodology. During the research, the methods of theory of railway operation, dynamic programming and mathematical statistics were used.

Findings. Research on the assembling process of car group to one track established the distribution parameters of the random variable of time spent for shunting. In the course of the research, the problem of choosing the optimal order of shunting operations during car assembling was formalized and solved as a problem of dynamic programming. The time spent for shunting work was chosen as the optimality criterion. The paper considers the possibility of approximating the data of calculation experiments by analytical dependencies. It was found out that the use of linear polynomials with interaction allows obtaining dependencies describing time standards with a relative accuracy of ±5 %.

Originality. The method is improved for developing the time standards for shunting work, which, unlike the existing one, is based on the performance of a series of calculation experiments, each of which solves the optimization problem of finding such an order of assembling cars that ensures minimum time consumption for shunting.

Practical value. The methods developed in the work and the dependencies obtained allow improving the quality of decisions made when developing technology and designing railway stations and sidings of industrial enterprises.

Keywords: *railway transport, railway station, siding, shunting work, time standards*

Introduction. Shunting is one of the basic elements of freight transportation process by railway [1, 2]. It is performed at public railway stations and on the tracks of industrial railway transport [3, 4]. Shunting work is related to significant consumption of time, fuel, and other resources. In this regard, research aimed at improving shunting operations is practically significant for railway transport. The important direction in the field of railway transport operation is the improvement of the standardizing methods of time spent for shunting operation. The standards that are currently used in railway transport include time standards for elementary operations such as, for example, replacement of cars, various preparatory and final operations. In addition, the standards set time expenditures for complex operations consisting of several elementary operations. Examples of complex operations are car sorting on the lead track, assembly of cars from several tracks, the completion of train formation, etc. As a rule, the same end result of a complex shunting operation can be achieved by implementing various options for performing elementary shunting operations. Therefore, time standards for complex operations should be determined taking into account the best operation order included in them. This work deals with one of the most widespread complexes of shunting operations – the assembly of cars from several tracks to one.

Literature review data and problem statement. Problems of the organization of shunting work attracted the interest of researchers even at the stage of railway transport formation. In particular, in the period of the 20-30s of the *20th* century, based on the results of analytical modeling by Professor Vasiliev I. I. the problem of optimizing the assembly of cars from several tracks to one was solved and published in monograph "Schedules and calculations for organizing railway transportation". Examples of different ways of assembling cars are shown in Fig. 1. At the same time, shunting work on assembling cars can be performed in the following ways:

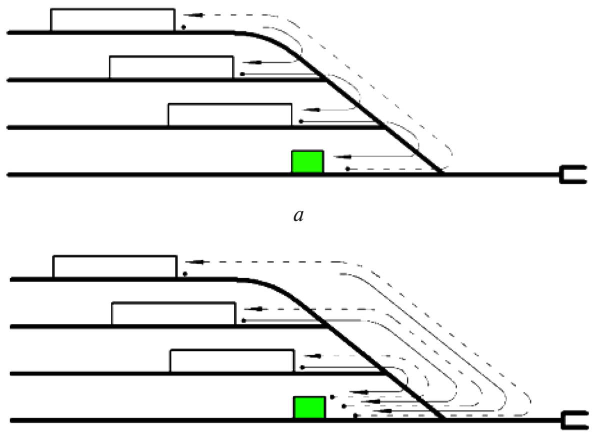
- rearranging groups of cars on the assembly track (Fig. 1, *a*);
- sequential join of car groups to the train (Fig. 1, *b*);
- combination of the methods described above.

According to the chosen method, the number of cars placed on the assembly track, the number of locomotive trips without cars, and the number of cars moved during each trip will differ. Based on the solution of the optimization problem by analytical methods, the optimal number of cars on the assembly track was determined and an expression was obtained for determining the minimum time spent on shunting movements

$$T_{ast} = a_h P + \frac{b_h M}{2} + \sqrt{2 a_l b_h M P}, \qquad (1)$$

where P is the number of tracks from which the cars are assembled; M is the number of cars that are rearranged to the assembly track; a_l is shunting parameter reflecting the time spent on the trip of a single shunting locomotive, min/run; a_h, b_h are shunting parameters reflecting the time expenditures for the trip of a shunting locomotive with a train, respectively for the locomotive itself and for each additional car, min/run and min/run/cars.

At the same time, the main assumption that simplified the formulation and solution of the problem and made it possible



a

b

Fig. 1. The ways of car assembling:

a – rearranging car groups on the assembly track; b – sequential join of car groups to the train

to obtain expression (1) was the assumption of a uniform distribution of cars along the tracks of their initial location.

After linearization of expression (1), a dependence was obtained, which is used for practical calculations of the duration of shunting operation for assembling cars in modern conditions

$$T_{asp} = UP + FM, \quad (2)$$

where U, F are the constant coefficients reflecting the standard time expenditures for rearranging the cars, respectively, min/track and min/car.

In 1957 in this form, the time standard for assembling M cars from P tracks was included into "Guidelines for technical regulation of shunting work" and is used to this day in "Methodical guidelines for determining time standards for shunting operations performed on railway transport". It should be noted that in contemporary guidelines, based on expression (2), a table was constructed, using which, in fact, the time for the car assembly is established during the development of operation technology of railway stations and technological processes for the operation of sidings of industrial enterprises.

The presented methodology was criticized for the following reasons:

- as a rule, there is a different number of cars on the different tracks;
- the number of cars located on the tracks and included in the shunting train can only take integer values;
- the statement that the calculation results of the duration of shunting work with the groups of medium-length cars correspond to the average duration of shunting work was not verified.

Simplifications adopted when solving the problem of standardizing the car assembly duration were caused by the limited possibilities of mathematical methods that were used to solve applied problems in the field of railway transport at the beginning of the *20th* century. In the second half of the *20th* century and in the early *21st* century, the methods of operations research and computer modeling began to be widely used to solve applied problems of organizing shunting work in railway transport. In particular, in the work by Blackburn [5], the problem of arranging cars by destination on a limited number of tracks is presented. The solution of the problem was achieved by the methods of graph theory. The methods for solving the problem of forming the outcoming traffic volume of multi-group trains from the incoming traffic volume of trains are presented in the works [6–10]. At the same time, in the work by Falsafain and Tamannaei [6], the method of dynamic programming was used to solve the problem; in the works by Dorpinghaus & Schrader [7], Beygang, et al. [8], Hansmann & Zimmermann [9] the graph theory methods were used; in the work by Bohlin, et al. [10] the linear integer programming method was used to solve the problem. As the purpose of optimization in the works [6–10], a minimum number of stages of shunting work was chosen. It should be noted that, as a rule, the quality of shunting work is estimated by time expenditures. At the same time, the number of stages of shunting work is important, but not the only factor affecting time consumption. The works [11, 12] are examples of solutions to the problem of minimizing time expenditures on shunting. The work by Kozachenko, et al. [11] describes the solution to the problem of minimizing the time expenditures for changing the car order in the train by reducing it to the search problem of the minimum distance between two vertices on the graph. The work by Jaehn, et al. [12] presents a solution to the problem of extracting freight cars from the staging track by the methods of linear integer programming. In both cases, the optimal solution can be obtained for a limited number of cars, since the complexity of the problem increases sharply with their increase. In the works by Hirashima [13, 14], the distance of movement of the shunting locomotive was used as an optimization criterion. Such a criterion is somewhat simplified, since with small distances of individual movements, considerable time is spent on acceleration and deceleration, however, it can be used with significant speed restrictions for shunting.

Another approach that is widely used in planning shunting work is related to the use of various simulation models to perform computer calculation experiments [15, 16]. In particular, such an approach is applied in the works by Ivic, et al. [17], Hirashima [18] when choosing the order of multi-group train formation, by Belosevic & Ivic [19] when solving the problem of forming the outcoming traffic volume of multi-group trains from the incoming traffic volume of trains, by Kozachenko, et al. [20] and Sivitsky, et al. [21] when solving the problem of technical and operational assessment of the railway station. The general scheme of conducting research in the works [17–21] is that the dependencies obtained in them are based on statistical processing of the results of calculation experiments. Herewith, in each individual experiment, the order of shunting work performing was established by heuristic methods. Such methods do not provide an exact solution to the problems, but in many cases, they allow obtaining solutions with sufficient accuracy for practical purposes.

Evaluation of the duration of shunting operations can be performed by various methods. In particular, in the work by Lashenyh, et al. [22] the duration of shunting movements is determined based on the analytical calculations. It should be noted that analytical models describe the movement of shunting trains in a simplified way. At the same time, the models using traction calculation methods, such as those described in the works by Kuznetsov, et al. [23] and Kozachenko, et al. [24], are rarely used when choosing the order of performing shunting operations due to their cumbersomeness.

The problems of the modern method for standardizing the duration of the operation of assembling cars on one track are related to the following. First of all, when solving the problems of managing the work of railway stations and railway transport of industrial enterprises, the main purpose is not to establish the operation duration, but to find such an order of shunting operation that ensures the achievement of minimum time expenditures for shunting work in specific operational conditions. The existing method of the duration of the shunting operation does not allow answering such questions. Secondly, when solving the problems of developing technology and designing railway stations and railway transport of industrial enterprises, the time standards are established for calculation conditions. According to expression (2), for the operation of assembling cars, these conditions are determined by the number of tracks P and the number of cars M. Taking into account the fact that the same number of cars can be placed on a given number of tracks in different ways, the time expenditures for assembling cars will be a random variable. The existing methodology allows estimating only its average value. At the same time, for the effective use of modern methods of simulation modeling when evaluating the technological and design decisions, it is also necessary to have estimates of the dispersion of the random variable relative to the average value. Therefore, the existing methods of standardizing the duration of assembling cars on one track require improvement.

Purpose and objectives of research. The purpose of the research is to improve the method for standardizing the duration of the shunting operation of assembling cars on one track. It can be achieved as a result of solving the following research problems:

- development of a method for searching the optimal order of assembling cars on one track;
- distribution parameters estimation of the random value of the duration of shunting operation of assembling cars on one track based on calculation experiments.

Research materials and methods. In this study, the following problem of car assembling is considered. A sorting yard with $P+1$ tracks, a lead and a turnout track is given. The track on which the cars need to be rearranged will be called the assembly track. The conventional consecutive numbers $i=\overline{1..P}$ are assigned to other tracks of the yard. It is assumed that there are groups of m_i cars on these tracks. The number of a car group corresponds to the number of the track on which it is located. The purpose of the shunting operation is rearranging all car groups from the tracks $i=\overline{1..P}$ to the assembly track. There are two variants for organizing the assembling of cars. According to the first variant, the cars must be assembled in such a way that the numbers of their groups in the assembled train form an increasing sequence. A similar requirement is put forward, for example, at the end of pick-up trains formation. According to the second variant, the groups of cars in the assembled train can be arranged in any order. This variant is possible, for example, when assembling the cars from the set-out tracks of the cargo area to transfer to the station. The shunting engine assembles the cars. In the initial state, the shunting engine is on the assembly track. Power restrictions of the shunting engine and the length of the turnout track are not taken into account. In comparison with the existing method for standardizing the duration of assembling the cars, such a formulation of the problem differs in detail of the car location on the tracks.

Different technical and operational indicators correspond to different procedures of car assembling. In this study, the total time expenditures T_{as} for shunting were chosen as a criterion for comparing variants for assembling cars and evaluating the effectiveness of shunting organization.

Car assembly includes two types of shunting trips:

- assembly trips – working trips with groups of cars;
- idle trips – idle trips of a single locomotive on a track where groups of cars are located.

The total time expenditures for shunting is the sum of the time spent on idle and assembly trips.

Let us consider the first version of the problem statement, when the groups of cars in the assembled train must be ordered. A series of shunting trips that starts from the idle trip of the shunting locomotive and ends with placing the cars on the assembly track will be called the stage of car assembling. One assembly stage may include several assembly trips. The minimum number of stages is 1 and corresponds to the case when assembly is performed by sequential joining all car groups to the train after entering the track $i = P$. The results of the previous research show that in the absence of traction force restrictions of the locomotive and the length of the tracks, the division of trains into parts when moving cars from one track to another is impractical. Therefore, the maximum number of car assembly stages is equal to P and corresponds to the case when assembly is carried out by replacing each car group to the assembly track.

Let z be the Boolean value indicating the idle trip of the shunting engine to start a new stage of assembly to the track i. Locomotive trip to the track with number P is mandatory, i.e. $z_P = 1$. For other tracks $1 \le i \le P$, the value of z_i is variable and is equal to 1 when the locomotive comes to the track i from the assembly track to start a new stage, and is equal to 0 when the locomotive joins cars from the i^{th} track to the train whose assembly has started from entering a track with a higher number than i. With this formulation, the problem has $P-1$ variable. More compactly, the set of variables z_i can be denoted by one binary number Z, the individual i^{th} digit of which corresponds to the value of z_i. This allows proceeding to the solution of the problem with one variable Z, the value of which is limited by the condition.

$$0 \le Z \le 2^P - 1. \tag{3}$$

The number Z will be called the order of car assembly.

Let us denote the number of assembly trips performed by the locomotive after entering the track i ($z_i = 1$) as x_i. The value x_i is restricted by the condition $1 \le x_i \le i$ and is determined by the number of zeros in the binary notation of the number $(2^P + Z)$ in the digits preceding the i^{th}. For example, if it is set $Z = 1001_2$ for a yard with 5 tracks, then

$$(2^P + Z)_2 = 11001,$$

and this means that the locomotive runs to track 1 and moves the cars to the assembly track ($z_1 = 1, x_1 = 1$); then the locomotive runs to track 4, makes two additional assembly trips ($z_4 = 1$, $x_4 = 3$) and rearranges the cars to the assembly track; at the end, the locomotive runs the track 5 and rearranges the cars to the assembly track ($z_5 = 1, x_5 = 1$).

The total time spent on shunting is defined as the sum of the time expenditures for the idle trips and assembly trips. In this research, as well as in the current standardizing methodology of the duration of shunting assembly, it is assumed that the duration of the locomotive idle trip is constant and equals a_l minutes, and the duration of the assembly trips depends linearly on the number of cars being rearranged

$$t_h = a_h + b_h m, \tag{4}$$

where m is the number of cars taking part in the shunting.

The time expenditures for shunting at the i^{th} stage of assembly can be determined by the expression

$$B_i(z_i, x_i) = \begin{cases} 0, & \text{at } z_i = 0 \\ a_l + a_h x_i + b_h M_i(x_i), & \text{at } z_i = 1 \end{cases}, \tag{5}$$

where $M_i(x_i)$ is the total number of cars moved during the assembly stage

$$M_i(x_i) = \sum_{r=1+i-x_i(Z)}^{i} (r + x_i - i) m_i. \tag{6}$$

The total time expenditures for assembling cars is the sum of the time spent for individual stages.

$$T_{as}(Z) = \sum_{i=1}^{P} B_i(z_i, x_i). \tag{7}$$

The total time expenditures for the movement of the shunting engine during assembly trips in expression (7) are constant and equal

$$a_h \sum_{i=1}^{P} x_i = a_h P.$$

Accordingly, expression (5) can be simplified and represented as

$$T_i(z_i, x_i) = \begin{cases} 0, & \text{at } z_i = 0 \\ a_l + b_h M_i(x_i) \end{cases}. \tag{8}$$

Finally, expression (7) can be represented as an objective function in the form of a condition

$$T_{as}(Z) = \dot{a}_h P + \sum_{i=1}^{P} T_i(z_i, x_i) \to \min. \tag{9}$$

Function (9) is additive. Considering that the values of Z are limited, the number of possible values of $T_{as}(Z)$ is also limited and the problem can be solved by enumeration of possibilities. Reducing the volume of possibilities can be achieved by reducing the task of choosing the order of car assembly on one track to the task of dynamic programming.

The dynamic programming problem is solved in P steps, which corresponds to the maximum possible number of assembly stages. Let us denote the minimum time expenditures for shunting work to assemble the cars from the sorting tracks from the track $i - x_i$ to the track P after entering the track i as $U_i(x_i)$. Considering that there are no tracks with higher numbers for the track $i = P$, then

$$U_P(x_P) = T_P(1, x_P). \quad (10)$$

For other tracks, conditionally minimum costs for car assembling can be defined as

$$U_i(x_i) = \min\left(T_i(1, x_i) + U_{i+1}(1);\ U_{i+1}(x_{i+1})\right) \quad \text{at} \quad i < P. \quad (11)$$

Conditionally optimal values of variables $z_i(x_i)$ corresponding to the tracks $1 \le i < P$ are determined by the formula

$$z_i(x_i) = \begin{cases} 1, & \text{if } T_i(x_i) + U_{i+1}(1) < U_{i+1}(x_{i+1}) \\ 0, & \text{if } T_i(x_i) + U_{i+1}(1) \ge U_{i+1}(x_{i+1}) \end{cases}. \quad (12)$$

Using expressions (10 and 11), the objective function (9) can be represented by a sequence of functions

$$\begin{aligned} &U_P(x_P) = T_P(x_P);\\ &U_{P-1}(x_{P-1}) = \min(T_{P-1}(1, x_{P-1}) + U_P(1); U_P(x_{P-1}+1));\\ &\ldots \qquad\qquad\qquad (13)\\ &U_1(x_1) = \min(T_1(1, x_1) + U_2(1); U_2(x_1+1));\\ &\min(T_{as}) = a_h P + U_1(x_1). \end{aligned}$$

After determining the minimum value of $T_{as}(Z)$, the value of the variable Z_{opt}, which provides it, is set according to the conditionally optimal values of the variables $z_i(x_i)$.

In the second variant of the problem setting, when groups of cars in the assembled train can be in any order, the minimum time spent on assembling cars can be set as the minimum time for assembling cars among the variants for which the number of cars on the tracks is the same, and only the numbers of the tracks differ.

The given method makes it possible to establish the optimal order, which ensures minimal time expenditures on assembling the train with the given initial location of its cars on the sorting tracks. Such a task is typical for operational management of railway stations. The proposed method is a direct optimization method and can be used both with simple methods for determining the time expenditures for transfer trips, such as (4), and with more complex ones, such as the method of traction calculations. This allows estimating the time expenditures on assembling cars with the accuracy required to solve a specific problem.

When performing technological and design calculations, the number of cars in the train $M = Sm_i$ and the number of tracks P, on which they are located, serve as the initial data for determining the time standard for shunting work on assembling cars. At the same time, the distribution of cars on the tracks (individual values of m_i) is unknown. The number of variants for placing M cars on P tracks is

$$Q = \frac{(M-1)!}{(M-P)!(P-1)!}. \quad (14)$$

In such conditions, the time expenditures for assembling a random train will represent a random variable. In order to set the parameters of the specified value, a complete enumeration of all possible variants for the location of M cars on P tracks can be performed. The distribution parameters of the random value of the duration of car assembly per one track can be established by calculating the minimum time of assembly of $T_{as,q}$ cars for each q^{th} variant $(q = \overline{1..Q})$ and statistical processing of the obtained values.

Research results. As an example, the problem of determining the order of train assembly of 30 cars placed on 5 tracks is considered. Table 1 shows two possible variants of the initial location out of 23,751 possible ones. In the calculations it was taken $a_l = 1.8$ min, $a_h = 1.8$ min, $b_h = 0.11$ min/car.

The search for the optimal order of assembling cars on one track for the variant 1 is illustrated in Table 2.

According to formula (9), the total time expenditures for assembling by cars will be $T_{as} = 18.14$ min, while $Z_{opt} = 10{,}102 =$ $= 1{,}010$. The optimal order of assembling cars for variant 2 is determined similarly. At the same time, $T_{as} = 15.20$ min, and $Z_{opt} = 0$. Thus, different optimal time and order of assembly operations will correspond to different variants for placing the same number of cars M on the same number of tracks P. The minimum time expenditures for the case when the assembled car groups can be in any order for variant 1 is 16.67 minutes, and for variant 2 – 15.20 minutes.

In contrast to the tasks of operational management of the work of railway stations and railway transport [25] of industrial enterprises, when information from a real object is used to calculate the car assembly duration, during the solution of the technology development tasks, the initial information for calculations is obtained from various models. At the same time, as a rule, the location of individual car groups on the tracks is unknown. Therefore, the train assembly time should be considered as a random variable. To estimate the parameters of this value, a computer program has been developed that implements the algorithm described in section 4 of the article and

Table 1

The initial number of cars on the tracks

Track number i		1	2	3	4	5
Number of cars m_i	Variant 1	2	3	14	1	10
	Variant 2	26	1	1	1	1

Table 2

Search for the optimal order of car assembling to one track for variant 1

i	Indicators	x_i				
		1	2	3	4	5
5	$T_5(1, x_5) = U_5(x_5)$	**2.90**	4.22	7.08	10.16	13.46
4	$T_4(1, x_4)$	2.02	**3.78**	5.76	7.96	–
	$T_4(1, x_4) + U_5(1)$	4.92	6.68	8.66	10.86	–
	$U_4(x_4)$	4.22	6.68	8.66	10.86	–
	$z_4(x_4)$	0	**1**	1	1	–
3	$T_3(1, x_3)$	3.34	5.10	7.08	–	–
	$T_3(1, x_3) + U_4(1)$	7.56	9.32	11.3	–	–
	$U_3(x_3)$	6.68	8.66	10.86	–	–
	$z_3(x_3)$	**0**	0	0	–	–
2	$T_2(1, x_2)$	2.02	**2.46**	–	–	–
	$T_2(1, x_2) + U_3(1)$	8.7	9.14	–	–	–
	$U_2(x_2)$	8.66	9.14	–	–	–
	$z_2(x_2)$	0	**1**	–	–	–
1	$T_1(1, x_1)$	2.02	–	–	–	–
	$T_1(1, x_1) + U_2(1)$	10.68	–	–	–	–
	$U_1(x_1)$	9.14	–	–	–	–
	$z_1(x_1)$	**0**	–	–	–	–

determines the time expenditures on shunting work to assemble cars for all possible location variants of a given number of cars M on a given number of tracks P. The distribution histogram of the random value of the assembly duration of $M = 30$ cars with $P = 5$ tracks (the specified conditions are similar to the numerical examples discussed above) is shown in Fig. 2. The random variable T_{as} has an asymmetric distribution with a negative skewness coefficient. At the same time, the mathematical expectation is $M[T_{as}]$ = 17.82 min, the mean square deviation $s[T_{as}]$ = 0.58 min, the minimum duration of train assembling (with the most favorable car location) is 15.20 minutes, and the maximum (with the least favorable car location) is 19.24 minutes. For comparison, the duration of car assembling determined by expression (1) is T_{ass} = 18.36 min.

In a similar way, the average time expenditures for other combinations of the number of cars and the number of tracks was determined. At the same time, the number of cars varied from 1 to 40, and the number of tracks from 1 to 10. A fragment of the table obtained for the case when the cars must be in a certain order in the assembled train is given in Table 3. Time standards in Table 3 allow setting the time expenditures on assembling cars in the same way as the corresponding table in "Methodical guidelines for determining time standards for shunting operations performed on railway transport".

To assess the calculation accuracy when using analytical formulas in this study, the relative error was used, the value of which was determined by the expression

$$\delta(P,M) = \frac{f(P,M) - M[T_{as}(P,M)]}{M[T_{as}(P,M)]}, \quad (15)$$

where $f(P,M)$ is the analytical dependency of the car assembly duration on the number of tracks and the number of cars, min.

The studies conducted show that the relative error when using formula (1) to determine the time expenditures on train assembling according to the group order is from –35 to +4 %. Positive error values are typical for conditions when a small number of cars are assembled from a small number of tracks. These errors are related to the fact that when deriving the expression (1) they ignored the fact that the number of cars in shunting trains and the number of assembly stages can only take integer values. As the numbers of cars and tracks increase,

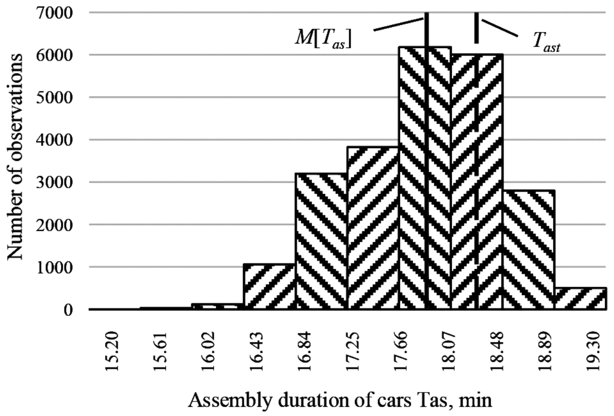


Fig. 2. Distribution histogram of the random value of the assembly duration of M = 30 cars with P = 5 tracks

the errors take on positive values. This is caused by the fact that when deriving expression (1), it was assumed that the cars are evenly distributed along the tracks. In fact, such an arrangement of cars is one of the most unfavorable. If there is no requirement to observe the order of car groups in the assembled train, the relative error when using formula (1) ranges from –35 to +9 %.

Examples of the obtained dependencies of the mean square deviation of time expenditures for assembling trains with ordered car groups on the number of tracks from which these cars are assembled and the number of cars being assembled are presented, respectively, in Figs. 3, *a*, *b*.

The value of the mean square deviation depends on the number of variants for placing M cars on P tracks and on the difference in the number of cars on the tracks.

Today, the duration of car assembling on one track is calculated according to a linear dependency (2). According to the current methodology, the values of the coefficients U = 1.8 min and F = 0.3 min/car are provided. With such coefficients, the calculation accuracy for the majority of combinations of the number of cars and tracks ranges within ±10 %. However, the limit of error reaches +73 and –27 %.

Table 3

Average time expenditures for car assembly complying with the group order in the train

Number of cars	Number of tracks									
	1	2	3	4	5	6	7	8	9	10
1	3.71	–	–	–	–	–	–	–	–	–
2	3.82	5.73	–	–	–	–	–	–	–	–
3	3.93	5.90	7.86	–	–	–	–	–	–	–
4	4.04	6.06	8.08	10.10	–	–	–	–	–	–
5	4.15	6.23	8.30	10.38	12.45	–	–	–	–	–
6	4.26	6.39	8.52	10.65	12.78	14.91	–	–	–	–
7	4.37	6.56	8.74	10.93	13.11	15.30	17.48	–	–	–
8	4.48	6.72	8.96	11.20	13.44	15.68	17.92	20.16	–	–
9	4.59	6.89	9.18	11.47	13.75	16.02	18.25	20.43	22.55	–
10	4.70	7.05	9.40	11.74	14.05	16.31	18.52	20.68	22.79	24.90
15	5.25	7.88	10.42	12.85	15.18	17.44	19.67	21.88	24.10	26.33
20	5.80	8.67	11.30	13.76	16.11	18.44	20.75	23.05	25.33	27.59
25	6.35	9.37	12.06	14.56	16.98	19.38	21.76	24.10	26.41	28.70
30	6.90	10.02	12.76	15.32	17.82	20.28	22.69	25.07	27.41	29.73
35	7.45	10.64	13.43	16.07	18.63	21.12	23.57	25.97	28.35	30.71
40	8.00	11.25	14.09	16.79	19.39	21.92	24.40	26.84	29.26	31.65

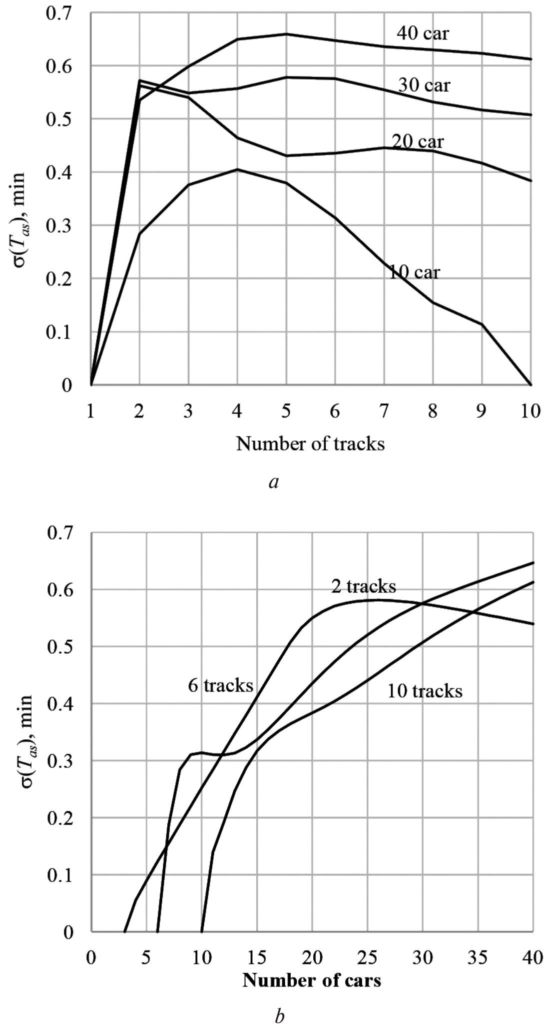


Fig. 3. Dependencies of the mean square deviation of the time spent on train assembling with ordered car groups:
a — on the number of tracks; b — on the number of cars

The error reaches an even greater value due to the entry in the table in [3] of time standards for ranges of 5 cars. To assess the possibility of approximating the results of calculation experiments by linear dependency, the coefficients of dependency (2) are determined using the following condition

$$\max\left|\delta(P,M)\right| \to \min, \quad P = \overline{1..10}, \quad M = \overline{1..40}. \qquad (16)$$

Condition (16) is satisfied by the coefficients $U = 2.82$ min and $F = 0.16$ min/car. At the same time, the relative error in individual calculations is ±20 %. Such accuracy is unacceptable for engineering calculations. The simplest analytical model that allows approximating the results of calculation experiments in Tables 3 and 4 with an accuracy of ±5 % is a polynomial of the first degree with the interaction of the following kind

$$T_{ass} = k + k_P P + k_M M + k_{PM} PM, \qquad (17)$$

where k, k_P, k_M, k_{PM} are the coefficients of statistical model.

Condition (16) is satisfied by the coefficients $k = 1.46$ min, $k_P = 2.04$ min/track, $k_M = 0.107$ min/car, $k_{PM} = 0.0161$ min/car/track.

Discussion of results. The conducted studies show that a number of successive simplifications were adopted during the development of modern time standards for shunting work on assembling cars on one track. As a result, the time standards according to the current methodology are set with a significant error. Originality of the work lies in the fact it improves the method for developing the time standards for shunting work, which, unlike the existing one, is based on the performance of a series of calculation experiments, each of which solves the optimization problem of finding such an order of assembling cars that ensures minimum time consumption for shunting. The problem of finding the optimal order of assembling cars in the work is formalized and solved as a problem of dynamic programming. For the first time, the dependencies of the mean square deviation of the time spent on assembling cars were obtained. The practical significance of the research is in the fact that the methods developed make it possible to improve the quality of solutions when developing the technology for existing and projected railway stations and sidings of industrial enterprises. Reference values of a_l, a_h and b_h coefficients are used in this work. At the same time, the technology of shunting at each station and siding has its own characteristics. In this regard, the goal of further research is to analyze the influence of local conditions on the time expenditures for assembling cars.

Conclusions. The conducted research allows us to draw the following conclusions.

1. When formalizing the task of finding the optimal order of assembling cars on one track, the number of the assembling order can be taken as a variable, and the time spent on shunting work can be taken as the objective function. The problem can be reduced to a problem of dynamic programming. The number of solution steps in this case is equal to the number of tracks from which the cars are assembled, and for each track one solves the issue of starting a new assembly stage or joining the train when assembling from tracks with higher numbers.

2. When developing the technology and designing railway stations and sidings, the location of a given number of cars on a given number of tracks should be considered as random. As a result, the time expenditures for car assembling make a random variable. Parameters of the random amount of time spent on car assembling can be obtained as a result of statistical processing of the results of calculation experiments. The studies performed show that the determination of time expenditures for shunting work based on the analytical dependency obtained for the conditions when there is the same number of cars on the tracks leads to significant errors. The value of the error in this case ranges from –35 to +4 % for cases when the car groups in the assembled train must be ordered and from –35 to +9 % for the case when the car groups in the assembled train can be in an arbitrary order.

3. As a result of the study, on the basis of calculation experiments, the tables of mathematical expectation and mean square deviation of time expenditures for shunting work for car assembling on one track were obtained. These tables are for the cases when the car groups in the assembled train must be ordered and when the car groups in the assembled train can be in an arbitrary order. The possibility of approximating the obtained data using analytical dependencies was evaluated. It shows that when using polynomials of the first degree with interaction, the accuracy of the results will be within ±5 %.

Conflict of interest. The authors declare that they have no conflict of interest in relation to this study, including financial, personal, authorship, or any other, that could affect the study and its results presented in this article.

References.

1. Fischer, S. (2022). Investigation of the Horizontal Track Geometry regarding Geogrid Reinforcement under Ballast. *Acta Polytechnica Hungarica*, *19*(3), 89-101. https://doi.org/10.12700/APH.19.3.2022.3.8.

2. Szalai, S., Szívós, B. F., Kurhan, D., Németh, A., Sysyn, M., & Fischer, S. (2023). Optimization of Surface Preparation and Painting Processes for Railway and Automotive Steel Sheets. *Infrastructures*, *8*(2), 28. https://doi.org/10.3390/infrastructures8020028.

3. Kou, L., Sysyn, M., Fischer, S., Liu, J., & Nabochenko, O. (2022). Optical Rail Surface Crack Detection Method Based on Semantic Segmentation Replacement for Magnetic Particle Inspection. *Sensors*, *22*(21), 8214. https://doi.org/10.3390/s22218214.

4. Fischer, S. (2022). Geogrid reinforcement of ballasted railway superstructure for stabilization of the railway track geometry – A case

study. *Geotextiles and Geomembranes*, *50*(5), 1036-1051. https://doi.org/10.1016/j.geotexmem.2022.05.005.
5. Blackburn, S. R. (2018). *Inglenook Shunting Puzzles*. ArXiv. https://doi.org/10.48550/arXiv.1810.07970.
6. Falsafain, H., & Tamannaei, M. (2019). A Novel Dynamic Programming Approach to the Train Marshalling Problem. *IEEE Transactions on Intelligent Transportation Systems*, 1-10. https://doi.org/10.1109/tits.2019.2898476.
7. Dorpinghaus, J., & Schrader, R. (2018). A graph-theoretic approach to the train marshalling problem. *Proceedings of the 2018 Federated Conference on Computer Science and Information Systems, 15*, 227-231. https://doi.org/10.15439/2018F26.
8. Beygang, K., Krumke, S. O., & Dahms, F. (2010). *Train Marshalling Problem-Algorithms and Bounds*. Retrieved from https://d-nb.info/1027389848/34.
9. Hansmann, R. S., Zimmermann, U. T., Krebs, H. J., & Jäger, W. (Eds.) (2008). *Optimal Sorting of Rolling Stock at Hump Yards. Mathematics – Key Technology for the Future. Berlin, Heidelberg: Springer*, 189-203. https://doi.org/10.1007/978-3-540-77203-3_14.
10. Bohlin, M., Gestrelius, S., Dahms, F., Mihalák, M., & Flier, H. (2016). Optimization Methods for Multistage Freight Train Formation. *Transportation Science*, *50*(3), 823-840. https://doi.org/10.1287/trsc.2014.0580.
11. Kozachenko, D., Bobrovskiy, V., Gera, B., Skovron, I., & Gorbova, A. (2021). An optimization method of the multi-group train formation at flat yards. *International Journal of Rail Transportation*, *9*(1), 61-78. https://doi.org/10.1080/23248378.2020.1732235.
12. Jaehn, F., Otto, A., & Seifried, K. (2018). Shunting operations at flat yards: retrieving freight railcars from storage tracks. *OR Spectrum*, *40*, 367-393. https://doi.org/10.1007/s00291-017-0495-x.
13. Hirashima, Y. (2011). A new design method for train marshaling evaluating the transfer distance of locomotive. *Intelligent Control and Innovative Computing*, 163-176. https://doi.org/10.1007/978-1-4614-1695-1_13.
14. Hirashima, Y. (2016). A reinforcement learning for marshaling of freight train considering collective motions. *Proceedings of the International MultiConference of Engineers and Computer Scientists*, *1*, 19-24. Retrieved from https://www.iaeng.org/publication/IMECS2016/IMECS2016_pp19-24.pdf.
15. Turpak, S. M., Taran, I. O., Fomin, O. V., & Tretiak, O. O. (2018). Logistic technology to deliver raw material for metallurgical production. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu,* (1), 162-169. https://doi.org/10.29202/nvngu/2018-1/3.
16. Saukenova, I., Oliskevych, M., Taran, I., Toktamyssova, A., Aliakbarkyzy, D., & Pelo, R. (2022). Optimization of schedules for early garbage collection and disposal in the megapolis. *Eastern-European Journal of Enterprise Technologies*, *1*(3-115), 13-23. https://doi.org/10.15587/1729-4061.2022.251082.
17. Ivic, M., Markovic, M., & Markovic, A. (2007). Effects of the application of conventional methods in the process of forming the pick-up trains. *Yugoslav Journal of Operations Research, 17*(2), 245-256. https://doi.org/10.2298/YJOR0702245I.
18. Hirashima, Y. (2013). A Reinforcement Learning for Train Marshaling Based on the Processing Time Considering Group Layout of Freight Cars. *IAENG Transactions on Electrical Engineering*, *1*, 229-243. https://doi.org/10.1142/9789814439084_0018.
19. Belosevic, I., & Ivic, M. (2017). Variable Neighborhood Search for Multistage Train Classification at Strategic Planning Level. *Computer-Aided Civil and Infrastructure Engineering*, *33*(3), 220-242. https://doi.org/10.1111/mice.12304.
20. Kozachenko, D., Verlan, A., & Korobyova, R. (2020). Improvement of graphical model of railway stations functioning. *2020 International Conference on Decision Aid Sciences and Application (DASA)*, 395-398. https://doi.org/10.1109/DASA51403.2020.9317139.
21. Sivitsky, D. A., Karasev, S. V., & Osipov, D. V. (2022). Methodology for Selecting the Multistage Methods of Train Classification and Design Parameters of Specialized Shunting Facilities Based on Modeling. *Transportation Research Procedia*, *61*, 323-332. https://doi.org/10.1016/j.trpro.2022.01.053.
22. Lashenyh, O., Turpak, S., Gritcay, S., Vasileva, L., & Ostroglyad, E. (2016). Development of mathematical models for planning the duration of shunting operations. *Eastern-European Journal of Enterprise Technologies*, *5/3*(83), 40-46. https://doi.org/10.15587/17294061.2016.80752.
23. Kuznetsov, V., Lyubarskyi, B., Kardas-Cinal, E., Yeritsyan, B., Riabov, I., & Rubanik, I. (2020). Recommendations for the selection of parameters for shunting locomotives. *Archives of Transport*, *56*(4), 119-133. https://doi.org/10.5604/01.3001.0014.5650.
24. Kozachenko, D., Dovbnia, M., Ochkasov, O., Serdiuk, V., Shepotenko, A., & Keršys, A. (2018). Rationale for Choosing the Type of Traction Rolling Stock for the Enterprise of Industrial Transport. *In Proceedings of 22nd International Scientific Conference. Transport Means*, *2018*(2), 991-995. Retrieved from https://transportmeans.ktu.edu/wp-content/uploads/sites/307/2018/02/Transport-means-II-A4-2018-09-25.pdf.
25. Németh, A., & Fischer, S. (2018). Investigation of glued insulated rail joints with special fiber-glass reinforced synthetic fishplates using in continuously welded tracks. *Pollack Periodica*, *13*(2), 77-86. https://doi.org/10.1556/606.2018.13.2.8.

Удосконалення методу нормування часу щодо збирання груп вагонів на одну колію

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Мета. Удосконалення методів нормування тривалості маневрової роботи зі збирання вагонів на одній колії. Це може бути досягнуто в результаті вирішення наступних завдань дослідження: розробка методу пошуку оптимального порядку збирання вагонів на одну колію; оцінка параметрів розподілу випадкової величини тривалості маневрової роботи зі збирання вагонів на одній колії на основі розрахункових експериментів.

Методика. У ході дослідження використовувалися методи теорії експлуатації залізниць, динамічного програмування й математичної статистики.

Результати. У ході дослідження процесу збирання груп вагонів на одну колію встановлені параметри розподілу випадкової величини часу, що витрачається на маневрову роботу. Задача вибору оптимального порядку маневрових операцій зі збирання вагонів була формалізована та вирішена як задача динамічного програмування. В якості критерію оптимальності обрано час, що витрачається на маневрову роботу. Розглянута можливість апроксимації даних розрахункових експериментів аналітичними залежностями. Встановлено, що використання лінійних поліномів із взаємодією дозволяє отримати залежності, що описують норми часу з відносною точністю ±5 %.

Наукова новизна. Полягає в тому, що в роботі удосконалено метод розробки нормативів часу на маневрову роботу, який, на відміну від існуючого, базується на проведенні серії розрахункових експериментів, кожен з яких розв'язує оптимізаційну задачу знаходження такого порядку збирання вагонів, що забезпечує мінімальні витрати часу на маневрову операцію.

Практична значимість. Розроблені в роботі методи та отримані залежності дозволяють підвищити якість рішень, що приймаються при розробці технології та при проектуванні залізничних станцій і під'їзних колій промислових підприємств.

Ключові слова: *залізничний транспорт, залізнична станція, під'їзна колія, маневрова робота, норми часу*

The manuscript was submitted 02.08.23.