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THE DISTRIBUTION OF MARSHALLING WORK OF INDUSTRIAL AND MAINLINE RAIL TRANSPORT

Summary. The article discusses the issue of effective distribution of work on formation of train network between the stations of industrial and mainline rail transport. The analysis is worked out of difficulties in the interaction of technological systems of railway transport of common and uncommon use and risks of the transport stream delays. The strategy for sorting of wagons and a complex of interconnected mathematical models is developed. The proposed solution method is based on step-by-step distribution of traffic volumes over the network through valid assignments of trains with subsequent calculation of the compromise management, taking into account the interests of each owner of transport infrastructure and each individual member of the transport and logistics chains.

1. INTRODUCTION

One of the fundamental problems of industrial logistics is the organization of flows of transport units serving the technological process of primary production, delivery of raw materials and components, and finished products departure of both individual enterprises as well as large industrial clusters. Improving management efficiency is possible by using the principles of logistics management through analysis and identification of technological and information imbalances and losses that contribute to the growth of transportation costs [1]. Currently, many industrial enterprises face the necessity to take strategic decisions concerning the effective distribution of sorting work between the stations of industrial and main railway transport. A significant effect on the future of the forwarding, transport and logistics sector will be based on the strategies chosen by the companies. One of the strategic decisions is to determine the transport fleet size, which can be supported by the use of make and buy decision-making [2].

Known methods of solution of problems of internal car traffic volumes organization at large industrial enterprises [3], as well as an extensive range of studies on the organization of traffic volumes on the main railway network [4-11], generalized in the guidelines [12].

The organization of car traffic volumes affects the interests of shippers, consignees, and carriers. The work of many foreign scientists is devoted to the evaluation of the effectiveness of the use of rolling stock in various ways of flow organization, as well as to the establishment of efficiency for each of the participants of the transportation process [13-19]. However, the distribution of sorting work in the interaction of industrial and mainline transport infrastructure has significant specificity.

There are various methods of solving the current scientific problems, such as the development of modern attractive tools for transport research [20, 21]. Milenkovič, Bojovič, Švadlenka and Melichar [22] present one of the most successful and most popular advanced control methods in the analysis of stochastic variables.

The decision of optimization tasks of transport operation technology in large industrial and transport nodes affects the expenses and income of each owner of transport infrastructure and each individual member of the transport and logistics chains. The presence of multiple objective functions and their semantic contents determines the status of these tasks by class task compromise control. In turn, such problems require decomposition into a number of subtasks of self-operation and coordination in complex dynamic systems with hierarchical control [23].

2. FEATURES OF A SUBSTANTIAL FORMULATION OF THE PROBLEM

2.1. Components of technology optimization

For interactive technological systems of industrial and mainline rail transport the following parameters must be justified:

1) rational organization of work of locomotive fleets (by rail carrier and the owner of the uncommon used railway track);
2) effective scheme of car traffic volumes organization and standards of weight and length of trains and shunting trains, circulating between the stations of railway infrastructures of common and uncommon use;
3) rational distribution of marshalling:

processing non-routed traffic volumes entering the railway line of uncommon use from the external network, and the formation of trains following to the industrial freight stations by the railway line of uncommon use and its contractors;

processing of traffic volumes coming from the industrial freight stations by the railway line of uncommon use and its contractors, and the formation of trains for the external network according to the train make-up plan and the unit train plan of the external network;

processing of empty car volumes coming from the industrial freight stations by the railway line of uncommon use and its contractors, and including them into trains for the loading station belonging to the railway line of uncommon use.

2.2. The dynamics of operational difficulties

Operational difficulties arising in the work of industrial and transport hubs have cyclical cause-and-effect relationships: (1) the excess of the rolling stock at freight terminals causes untimely departure of cars from the places of loading and unloading, (2) delay of the wagons' departure from cargo stations causes delays of the delivery of wagons to the places of loading and unloading, (3) because of supply delays, there occur delays of departure of wagons from marshalling yards, (4) excess rolling stock in the rail yard does not allow time to dispatch the cars from the cargo terminals, and (5) the delay of departure of wagons from cargo stations causes an excess of rolling stock at terminals.

To overcome the difficulties and to prevent their further work, it is necessary to eliminate the shortage of capacity of the track development. To do this, there are two ways: the extensive (physical expansion of the track development) and intensive (improved technology, replacing reserves of track capacity by management reserves) [24, 25].

2.3. The strategy of marshalling

Technology of the sorting work control in the industrial and transport hub node includes various strategies of marshalling:

1) According to the sorting tracks, specialized for stations of destination of the trains: this strategy ensures a minimal amount of additional sorting of cars. In this case, there is no agreement with the requirement of wagons at the destination points.
2) Under the requirement of wagons at the destination points: when this is achieved, there is full alignment with the requirement of wagons at the destination points. However, there is maximum amount of additional shunting work.

3) Mixed strategy: different strategies of sorting cars provide different levels of cars filling infrastructure and, therefore, different reliability levels for the exchange of wagons between the main and industrial railway transport.

2.4. The risks of delay in traffic flow

Consider two interacting rail network polygons A and B (which in general case may not be contiguous or belong to different railway infrastructures of common and uncommon use).

If the polygon A increases the level of organization of the traffic stream, next to the polygon B, in space (on destinations, weight and length of trains) and in time (at the rate of supply trains), then polygon A spends its infrastructure and time resources. Polygon B then receives the savings of its respective resources, owing to the higher orderliness of the traffic flow, and the less need for processing capacity and storage capacity of the track development.

In turn, polygon A reduces the risk of a delay of the traffic flow by polygon B, that is, for itself, it reduces the probability of a situation where the economic losses of the polygon A exceeds the valuation of the spent resources.

Therefore, the organization of interaction between the mainline and industrial railway transport requires for the evaluation of considered risks, which may be more meaningful than the payment received from partner in the process of transportation for additional service to streamline the flow of transmitted transport units.

3. COMPLEX OF MATHEMATICAL MODELS

The solution to the problem of the distribution of the sorting operation of industrial and mainline rail transport is based on the application of a complex of interconnected mathematical models (tab. 1).

The optimization mode provides a set of values of the following controlled variables:

X – destinations of freight trains, generated by the stations of external network, freight stations of the private railroad and the selected stations of concentration in the marshalling work;

W – standards of weight and length of freight trains with a traction support;

G – the attachment of traffic volumes to the destinations of freight trains;

S – routes of the freight trains on the rail network.

Evaluation mode options generate a set of values for the following performance indicators:

- journey of trains, wagons and locomotives;
- car fleets to their owners;
- fleets of train and shunting locomotives and locomotive crews state by industrial and mainline rail transport;
- dimensions of freight train movement on the stretch between stations at industrial and mainline rail transport;
- fuel and energy resources; and
- operating costs.

The restriction system must ensure compliance with the decision of problems of a number of necessary conditions:

- infrastructure related to bandwidth and the track storage capacity of the rail network;
- resource associated with the value of the resources available locomotive and car fleets; and
- logistics associated with the valid modes of the movement of traffic flows on the rail network, including the valid time of the network and its elements.

Table 1

Complex of mathematical models

Class of models	Obtained results
Models of analysis of statistics and forecasting	Dynamics and structure of transport flows
Static network flow model	Distribution of traffic flows
Dynamic network flow models	Check the stability and periodic adjustment of decisions
Simulation models of transport facilities	The performance of the network elements.

The objective function cannot be written as a simple sum of the costs associated with different flows of trains and of technical and technological parameters of the components of the industrial and transport hub. These costs are different participants of the transportation process and require decomposition into a number of one-criterion tasks with subsequent coordination of the results.

In general, the technology options of marshalling work and the transfer movement in the industrial and transport hub are evaluated cost functions of a railway carrier

$$R_1 = R_1^W + R_1^L + R_1^D = f_1(X, W, G, S, M, T, Z)$$

and the owner of the railway line of uncommon use

$$R_2 = R_2^W + R_2^L + R_2^D = f_2(X, W, G, S, M, T, Z),$$

where R_i^W – the costs of i-th participant of transport services connected with the maintenance of their cars, the use of borrowed cars and to pay a fine related to the car fleet; R_i^L – the costs of i-th participant of transport services related to the content of their own and others' use of locomotives and locomotive crews; R_2^D - additional customizable option costs (+) of *i*-th participant of transport services, including losses from low reliability (delay of delivery and failure of the planned loading) or savings (–), including unit trains efficiency; ***M*** – locomotive fleets by the railroad carrier and the owner of the railway line of uncommon use; ***T*** – timing parameters of technology; and ***Z*** – price parameters.

For both the mainline and industrial transport system (in the General case – for the i-th participant of the transport service), the probability of exceeding losses in the financial result of $\boldsymbol{A_i}$ over cost $\boldsymbol{R_i}$ requires minimization. Consequently, there is a P-model of stochastic programming (in terms of [26-27]) with objective function the minimization of the probability of exceeding the value of $\boldsymbol{A_i}$ on $\boldsymbol{R_i}$:

$$P[A_i > R_i(Y_i)] \rightarrow min \ ,$$

restrictions on resources involved

$$Y_i \leq Y_i^*$$

and allowable losses in the financial result

$$M[R_i(H_A, H_S, H_D)] \leq R_{max} \ ,$$

where $\boldsymbol{H_A}$ – the reliability of delivery terms of freight and empty cars; $\boldsymbol{H_S}$ – the reliability of supplying by cargo loading resources to received orders for transportation; and $\boldsymbol{H_D}$ – the reliability of supplying by traction resources to train departures from technical and cargo stations.

Valid values for the reliability parameters are the result of the solving of the technical and economic problems. It must be solved simultaneously for all three components of the reliability of freight traffic, to ensure shared resources are used. There is a M- model of stochastic programming (in terms of [26-27]): among the possible values of $H_A \leq 1, H_S \leq 1, H_D \leq 1$, it is necessary to find the set of values

$$\{H_A^*; H_S^*; H_D^*\}$$

providing a minimum of mathematical expectation of total losses in the financial result

$$F = M[R_i(H_A^*, H_S^*, H_D^*)] \rightarrow min$$

in compliance with the restrictions on available resources

$$Y_i \leq Y_i^* \ .$$

$\boldsymbol{Y_i}$ is a vector-function of controlled variables of the task, characterizing the infrastructure resources (processing ability of sorting complexes and cargo terminals, storage and regulating capacity of the track development, carrying capacity of stations, railway sections and intra-hub moves) and transportation resources (fleets of rolling stock and contingent of locomotive crews).

Loss in the financial result $\boldsymbol{R_i}$ takes into account the additional costs associated with providing reliability in the face of existing limitations, and loss of income associated with risk of penalty payments for the improper performance of obligations under the transportation process and risks of reducing the revenue receipts due to the failure of the shippers from rail services.

4. BASIC ALGORITHMS

The considered problems are combinatorial optimization problems, the character of which is due to the non-linearity and integer number of components of the objective function and constraints. They belong to the class of NP-complete problems [28], for which there are rigorous optimization algorithms. Therefore, the optimization mode should provide an approximate search of the baseline solution (step-by-step distribution of traffic flows over the network) and a number of heuristic procedures to improve the basic solution.

4.1. The calculation of the basic solution.

To calculate the basic solution, the algorithms developed as part of the method of step-by-step distribution of car traffic volumes on the network of permissible train destinations [29] were used.

It is necessary to provide a calculation of loading and performance of all the elements of the rail network. For this purpose, a network of crew districts and technical stations is "superimposed" on the model of the road network consisting of sections and stations. In the course of calculations on a network of crew districts and technical stations the network of train assignments with their characteristics shall, in turn, "overlay".

The main steps of calculation are the basic plan of formation and the number of its adjustments.

The baseline is calculated according to the algorithm of step-by-step distribution of traffic volumes on the network of valid assignments of the train formation plan:

Step 1. The ordering of the original jets of traffic volumes in descending order of power.

Step 2. The calculation of costs for the arcs of a network of valid assignments.

Step 3. The choice of assignments of the train formation plan for the car traffic flow from the station of origin to station of repayment using the program search the path of minimum cost in the network of allowable assignments.

Step 4. Checking of constraints and the calculation of penalties in their violation.

Step 5. Recalculation of costs on the arcs of a network the valid assignments using non-linear dependency of the costs on the value of the transmitted wagon flow.

Step 6. Checking for traffic volumes that are not routed over the network of destinations, with repetition (if any) steps 3 – 5.

Step 7. Fixing of train assignment which traffic volumes routed in the base solution.

During the patch of car traffic flow from each station of origin, the route by the train formation plan is determined to each destination station, and the destinations of trains and stations of the processing are identified on the route. In turn, for each assignment to construct a sequence of trains locomotive crews work areas, which should train this purpose, the station walkable transit trains without processing are identified.

Before routing of each next car traffic flow, it is necessary to check the execution constraints for each element of the network graph assignments. Then to calculate costs for those elements where the constraints are not met, the costs will increase.

In the calculations, it is necessary to apply a flexible system of penalties, that is, to prevent the possibility of violation of some of them (for example, minor overloading of hump, reception yard, sections) and, on the contrary, strict compliance with the restrictions (on the number of generated appointments).

After calculating the base variant of the plan of formation, a number of restrictions and logical conditions are checked, which can be realized only after the laying of all streams of traffic volumes and the definition of all appointments formation plan, with interactive adjustment of solutions, including the following:

elimination of loops in the routes of traffic volumes across the network of crew districts (under the "loop" route of the flow is understood here as a part of the path, the beginning and the end of which is one and the same station);

relaying of the traffic volumes that do not meet the condition of "tree-like" of following traffic volumes on appointments [29];

deletion of the "weak" destinations that do not meet the minimum capacity, with the calculation of new routes to be followed by the appointment of all traffic volumes, which were attached to remote destinations; and

the disaggregation of appointments with a capacity exceeding by technologist, with the release of "long" appointments.

4.2. The interactive procedure to improve the basic solution

The choice of marshalling work distribution options is performed on the basis of algorithms to find compromise control based on the criteria of each of the subsystems of the decentralized control of cargo and traffic volumes. To do this, the values of controlled variables to ensure a given level of quality of work of the subsystems, based on the required quality of operation of the system as a whole, are determined.

Interactive procedures provide the technologist the ability to set preferences on the set of possible solutions in the form of the following:

the required values of the objective functions and the permissible limits of ε-neighborhood of these values (or their changes) and

weighting factors that specify preferences in the objective function and in the space of constraints (the latter determines the degree of hardness of penalties for exceeding limits).

When calculating the compromise control, technologist ranks the objective functions $\boldsymbol{R_1},\ldots,\boldsymbol{R_i}$ and assigns acceptable concessions $\Delta\boldsymbol{R_1},\ldots,\Delta\boldsymbol{R_i}$ from their values. Further, the optimized value of the objective function $\boldsymbol{R_1}$; when it was found the value of R_1^* is optimized value of the objective function $\boldsymbol{R_2}$ with the restrictions

$$\begin{cases} R_1 \le R_1^* + \Delta R_1\,, & if\ R_1 \to min \\ R_1 \ge R_1^* - \Delta R_1\,, & if\ R_1 \to max \end{cases},$$

etc.

5. EXAMPLE OF PRACTICAL APPLICATION

The large metallurgical plant has an internal railway network, including the factory marshalling yard B (Fig. 1) and 17 freight and technological railway stations. This network has connections to the network of JSC Russian Railways (RZD) at two stations.

All marshalling work was concentrated at station B. In conditions of high utilization of devices, it caused large delays in traffic flows. Marshalling yard A, owned by RZD, has a large reserve capacity. The inclusion of station A in the work of transport maintenance of the plant will reduce delays and increase the reliability of operational work and the safety of train traffic. However, this redistribution of marshalling work will cause an increase in the journey of trains and wagons. Therefore, the variants for distributing marshalling work need a technical and economic assessment that takes into account the interests of both RZD and the metallurgical plant.

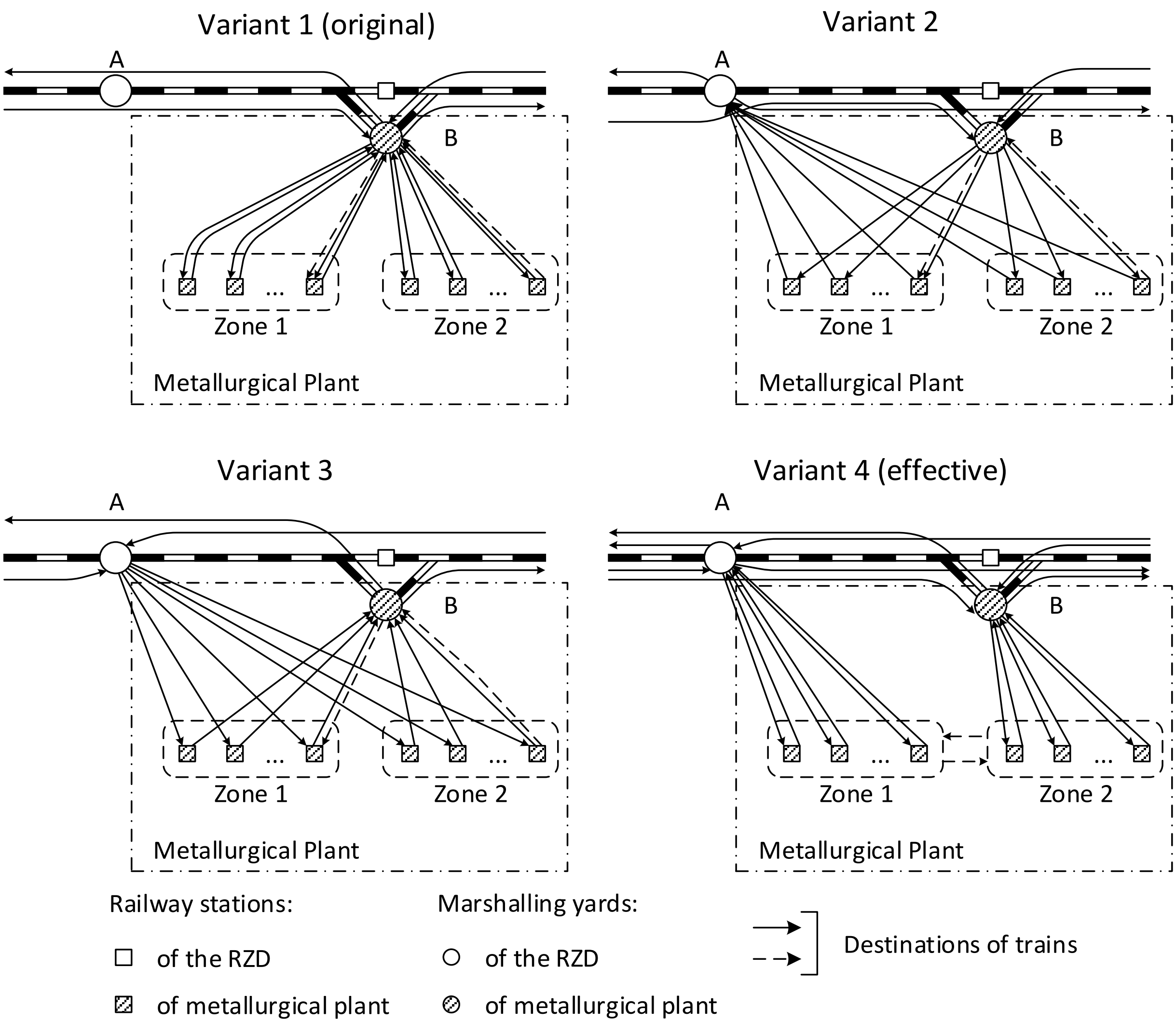

Fig. 1. Variants of distribution of marshalling work

There are four basic schemes for the distribution of sorting work (see Fig. 1). In variant 1 (existing), station A does not participate in the work with wagon flows of the plant, which are not included in block trains. In variant 2, station B processes non-routed wagons from the external network to the plant, and station A - wagons from the plant to the external network. In variant 3, on the contrary, station B processes the car flows following from the plant to the external network, and station A - the wagons from the external network to the plant. In both variants 2 and 3, station B processes empty cars coming from the freight stations of the plant and directed for loading (their running is shown in Fig. 1 by dashed arrows).

The main disadvantage of variants 2 and 3 is increasing of the journey not only of organized trains, but also single locomotives of RZD and the plant between stations A and B.

Variant 4 provides the division of freight stations of the plant into zones of gravitation, respectively, to marshalling yards A and B. Each of these two marshalling yards processes wagons both on arrival to the plant and on departure from the plant for stations of its gravity zone. In this variant, the transfer of empty wagons for loading is kept between freight stations of different gravity zones.

Tab. 2 shows the main indicators of variants 2, 3 and 4 in comparison with the existing variant 1.

The data of tab. 2 show that variant 4 is the most effective for both Russian Railways and the plant. Variant 3 is the most irrational.

Table 2

Indicators for the distribution of marshalling work

Indicators	The values of the indicators (± to variant 1) according to the variants		
	2	3	4
Processing on the sorting humps, wagon / day	+289	–	–
Journey поездов, of trains, train-km / day	+22,8	+105,2	–1,9
Single runs of locomotives, locomotive-km / day:			
of RZD	+35	+28	–
of plant	+87,5	+83	–21
Required fleet of locomotives:			
of RZD	+1	+1	–
of plant	+1	+1	–
Fleet of freight cars on responsibility:			
of RZD	+136	+43	–74
of plant	+44	+96	–190
Operating costs, mln. rubles / year:			
of RZD	+52,4	+74,5	–27,2
of plant	+32,7	+144,7	–170,2

6. CONCLUSION

The working ability and efficiency of the proposed methods is verified through the development of unified technological processes for a number of large industrial enterprises.

A positive issue of the implementation is the decision on the inclusion of these results to the project of methodology for the working out of unified technological processes of work of the uncommon use railway line and the junction railway station, which is prepared on the initiative of JSC "Russian Railways" and submitted to the Ministry of transport of Russia.

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