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METHODS OF SUBSTANTIATION OF SPECIALIZATION OF RAILWAY LINES

Summary. The article proposes methodological principles for substantiating the specialization of main railway lines based on the primary types of passenger or freight traffic in order to improve the level of transport services, economic efficiency, and reliability of the transportation process. The search for a solution to the problem provides a rational distribution of transport flows and investment measures, with the subsequent finding of a compromised operation for a set of effective alternatives.

1. INTRODUCTION

Specialization of railway lines is one of the most important directions for ensuring competitiveness, efficiency, and reliability of modern rail transport. JSC RZD adopted the document entitled «RZD Holding's Strategy up to 2030» which defined the major lines and instruments to reach the goals for the Russian railways. One of the key areas of research aimed to support JSC RZD efficiency growth is the development of scientifically grounded recommendations on how to improve traffic capacity and how to control operations over railway lines with considerations to the planned labeling of the lines by classes [1].

The effect-forming factors and objectives of specialization of the main railway lines are formulated in the concept [2]. However, these objectives are not achieved automatically, through physical isolation of passenger and freight traffic from each other.

In general, the concentration and specialization of production are effective with the growth of its volumes and quality requirements. Transportation production is no exception. The specialization of railway lines is a complex technical and economic task, the solution of which affects the costs and incomes of independent participants in transport and logistics chains in both freight and passenger transportation (Fig. 1). For this problem, multi-criteria statements optimizing the internal control actions of the transport subsystems (the self-management problem in terms of [3]) and the interaction of the subsystems (the coordination problem in terms of [3]) should be recorded.

Freight flow management in rail systems involves multicommodity flows on a network complicated by node activities (queueing and classification of cars at marshalling yards [4]). The decision should take into account 1) organizational-economic structure of rail transportation and 2) various characteristics and dynamics of traffic flows. For example, the Central Railway Line in Poland, which was created to link industrial Silesia with the center of the country and the seaports of the Baltic coast, today completely changed its specialization from freight to fast passenger transportation. Program of development of railway transport system as a process of preparation of the desired States of the system in individual years. For these purposes, it is possible to use a modular principle of development and specialization of railway lines [5].

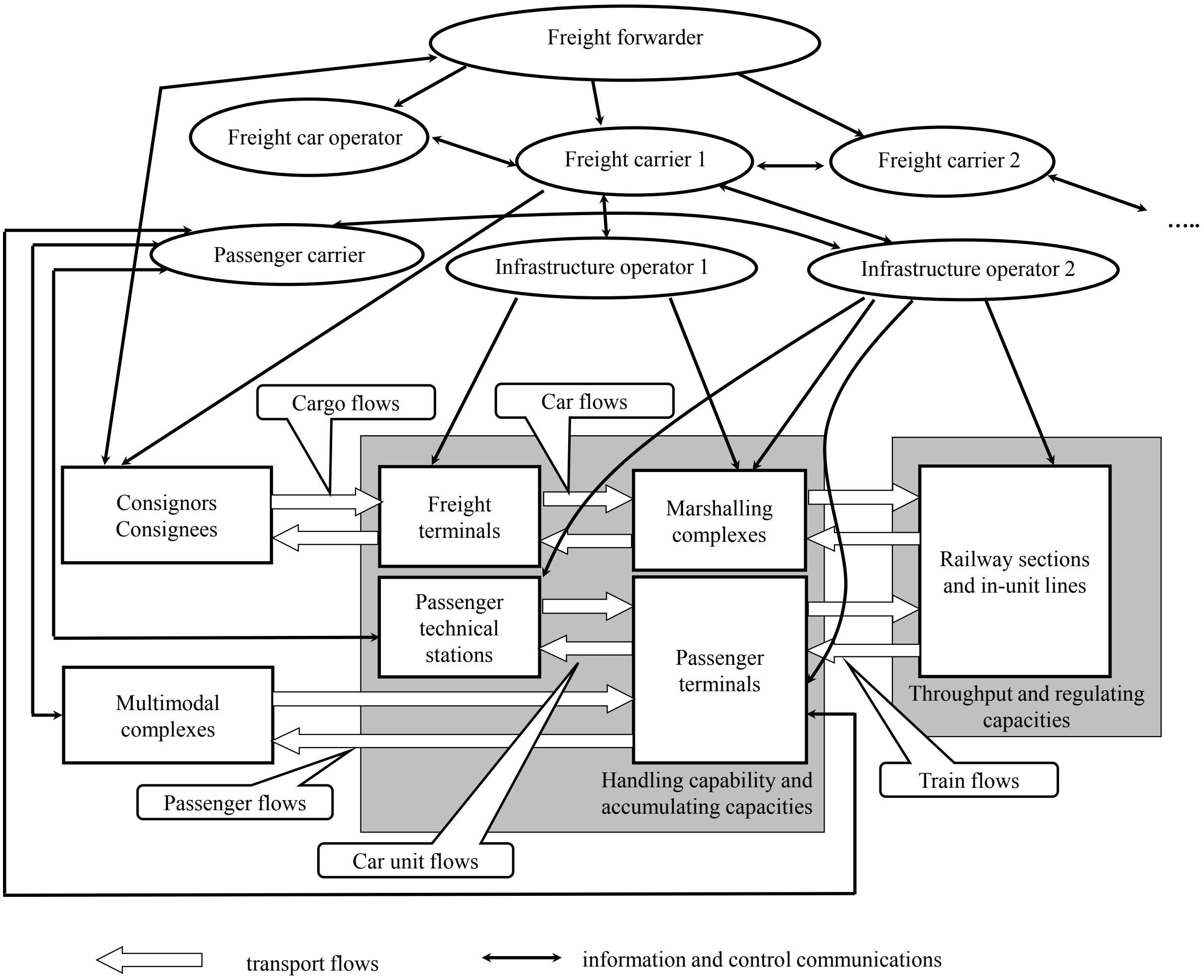

Fig. 1. Structure of interaction between participants in the transportation process

A discrete intermodal network design problem lies in the definition of determination of whether or not to build up or expand a link to minimize the total operating cost of carriers and hub operators under a general route choice model of intermodal operators. The problem can be formulated as a mixed-integer nonlinear and non-convex program that involves congestion effects, piecewise linear cost functions, and a fixed-point constraint [6].

In the conditions of the existing railway network, the specialization of railway lines provides efficient modes of their operation, based on the weight ranges and speed of handling passenger and freight trains. Universal multi-criteria evaluation system of route ensures rational choice of heavyweight loads routes of rail transport [7].

On the directions of the primary passenger traffic with the permissible speeds V ≥ 120 km/h, pass of container and other specialized freight trains with an increased schedule speed is effective. Pass of freight trains weighing $Q \geq 6000$ tons on such lines will cause high costs of repair and current maintenance of the infrastructure and significant difficulties in train operation.

On the network of the Russian Railways, unified polygon norms for the weight of freight trains of 6000-6300 tons and lengths of freight trains 995-1000 m are established. The infrastructure of lines of predominantly freight traffic ensures the movement of freight and passenger trains with the same permissible speeds. At the same time, convenient time of departure and arrival should be provided for passengers.

The evaluation of railway line capacity is an important problem, which affects the majority of problems in rail transportation planning. Multi-criteria problem should depict the dependencies of time and cost parameters on the loading of infrastructure elements. The problem can be formulated as a multicommodity network design model on a space-discrete time network [8]. Other analytical approach is the modelling of more complex train paths whereby each section can be visited many times in the course of a train's journey [9]. Given a certain demand matrix, the Non-Linear Programming (MINLP) model determines the most appropriate frequency and train capacity for each line taking into account infrastructure capacity constraints, allocating lines to tracks while assigning passengers to lines [10].

Problems in combinatorial optimization can be viewed as searching for best element in a discrete set. Business continuity is optimized by real-time traffic management, maximizing capacity, conserving energy, and minimizing inconvenience to the passenger and the freight user [11]. An analytical framework based on discrete Likelihood Maximization techniques provides estimates of operational level data of Queuing models and Transportation networks based on snapshots of data on movements of commodities in a network [12]. The objective function of maximizing the average daily financial result relies heavily on the integration of logistics activities with an improved management of revenues. The operational policies chosen by the carrier have an important impact on the network yield and thus on global profitability [13].

First, as a manageable variable is to minimize the number of movements required to arrange all the cars so that further relocations are not necessary. To solve the Pre-Marshalling Problem, a heuristic solution method can be used [14]. The goal is to find the optimal route for this shunting engine with respect to all constraints applicable to movements in a shunting yard [15].

Second, it has become imperative for rail systems to optimize the fleet size and freight car allocation in the presence of uncertainty. The problem can be considered as the problem of finding an optimal fuzzy regulator for a fuzzy linear system with fuzzy quadratic performance index and fuzzy random initial conditions [16]. Developed dynamic model of loaded and empty rail freight car flows explicitly treats state, control, and station capacity constraints in presence of various freight car types under the condition of partial substitutability among them. Demands and traveling times are considered as random variables [17].

2. RESEARCH OF THE PARAMETERS OF THE SOLUTION

The specialization of main railway lines has 3 principal schemes:

1) the construction of 3 and 4 main tracks with their specialization in terms of weight ranges and speed of trains - the BCDE line in Fig. 2a (this scheme requires significant investment in infrastructure but reduces the need for investment in rolling stock and operating costs for transportation activities by preserving efficient routes for traffic flows);
2) specialization of existing combined lines for weight ranges and speed of trains (Fig. 2b) - BCDE line for passenger trains with permissible speeds $V \geq 160$ - 200 km/h and accelerated freight trains and AFGHE line for heavy freight trains and passenger trains with $V \leq 90$ km/h (this scheme is much cheaper to invest in infrastructure, but changing the route of transport flows leads to a change in the need for rolling stock, operating costs, and most importantly, the conditions of transport services);
3) combined scheme, including the construction of separate connecting lines - a new section GD and a four-track section DE in Fig. 2c.

The problem of constructing specialized high-speed lines for $V \geq 300$ km/h requires independent consideration.

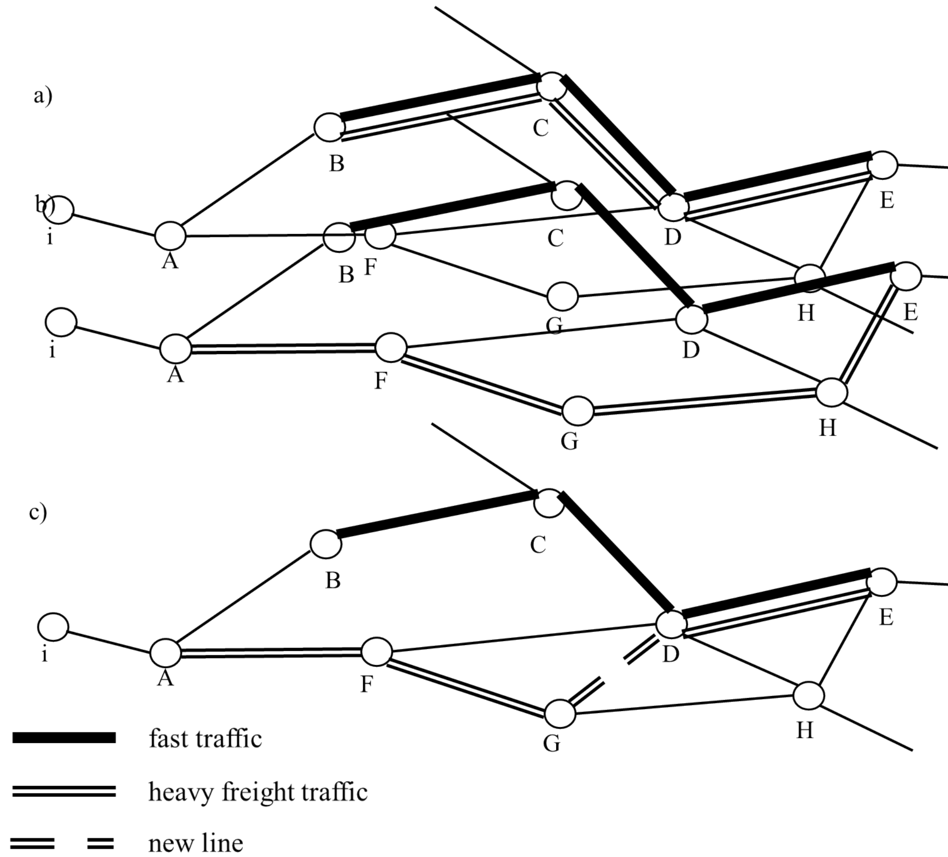

Fig. 2. Principal schemes for the specialization of main railway lines

There are different models of specialization of railway lines and the transportation. For example, in Germany, there are 3 types of train lines:

- dedicated passenger lines (uniform operation pattern, different stopping patterns, and different train types and speeds),
- freight line, and
- mixed passenger and freight lines.

Mixed railway line comprises 74% of the entire rail network. The contrary view of such a universal specialization is a significant increase in maintenance costs.

Fig. 2 shows that for a traffic flow from node i to node j, the shortest route is i – A – F – D – E – j. Movement along specialized lines increases the distance of the passenger flow by $\Delta l_{ps(ij)}$ km, the cargo flow by $\Delta l_{fr(ij)}$ km. The increase in the distance travel will be justified if there the financial results of the participants in the transportation process have been improved;

the restrictions on the permissible level of transportation process reliability are observed; and the restrictions on the permissible level of maneuverability of the railway polygon have been met, that is, the permissible values of delays in transport flows will not be exceeded, which is ensured by the additional development of capacity of the tracks in the stations and the additional throughput of the sections.

At the same time, the cost groups that depend on the specialization option for the lines *X*, the traffic flows *N*, the technologies for their organization and movement *Y* are taken into account:

- operating costs for maintaining the infrastructure $E_1(X, N, Y)$;
- operating costs associated with downtime and terminal handling of traffic flows $E_2(X, N, Y)$;
- operating costs for the movement of trains $E_3(X, N, Y)$;
- investments related to the strengthening of the capacity of existing infrastructure facilities and the construction of new ones $K_1(X, N, Y)$; and
- investments to rolling stock $K_2(X, N, Y)$.

The product lines according to the classes of transport services in passenger and freight traffic are characterized by the presence or absence of special requirements for rolling stock, infrastructure, and reliability of operational work with varying degrees of influence on cost parameters (tab. 1).

Table 1

Product lines for transport service classes in passenger and freight traffic

Classes of transport services	Availability of special requirements			
	to infrastructure parameters	to locomotives	to wagons	to reliability of operational work
Freight traffic				
in unit trains	+	+	–	+
with a given frequency of train handling	–	–	–	+
with given norms of weight and length of trains (dimensions of consignments)	+	+	+	–
with a given speed route	+	+	+	+
with the coordination of the time for the supply of trains and groups of wagons to designated points	–	–	–	+
Passenger traffic				
with a given frequency of train handling	–	–	–	+
with a given speed route	+	+	+	+
with the coordination of time of departure and arrival on designated points	–	+	–	+

The revenues of transportation for JSC "RZD" depend on the "price of carriage", which is going to the owner (operator), and the rate, which can pay the consignor. Improving the quality of transport service and better management of cars can attract additional volumes of cargo to railway transportation.

The value of the traffic flow generally contains two components: a component that does not depend on the results of solving the problem of line specialization and which depends on these results. For this component, the value of the traffic flow is the reaction of passengers and consignors to the speed, reliability, regularity, and cost of transportation achieved as a result of solving the problem of line specialization:

$$N_{ij} = N_{ij}^{*} + N_{ij}^{**}(X,Y) \tag{1}$$

The factor that should be considered for passenger trains and freight trains of fixed schedule is the frequency of cruising, and for the rest of freight trains, monthly and daily unevenness of traffic.

The flows and dimensions of the movement of freight and passenger trains are subject to consideration:

- average per day, to determine the operational and economic indicators in general for the billing period, and
- maximum, to verify the implementation of infrastructure and resource constraints.

3. PROBLEM STATEMENT

3.1. General solution sequence

The search for a solution to the problem of specialization of railway lines (Fig. 3) provides for a number of steps.

1) The topology of the railway network and the ranges of weight and speed of freight and passenger trains are specified. Their combinations generate alternatives to the specialization of railway lines.
2) The product lines for passenger and freight transportation are specified. Their combinations generate traffic flows for the given classes of transport services.
3) The process of distribution of transport flows and investment measures is carried out for each of the alternatives of line specialization with the calculation of a set of controllable variables and values of independent objective functions.
4) Post-optimization analysis of the results provides a comparison of the indices of the calculated options with each other and with the current transportation technology and determines the need for a repetition of the optimization calculation based on the specified parameters.
1) At the same time, changes should be evaluated in the technology of movement of traffic flows, in the degree of implementation of restrictions, in the amount of work and indicators of stations and sections; and in fleets of rolling stock.
5) A group of promising solutions that satisfy specified constraints serve as an input to the choice of compromise operation, the results of which should be acceptable to the interacting transport participants (see Fig. 1).

To calculate the natural and cost parameters, the railway network should be described as a set of interrelated mathematical models characterizing the following: 1) operation points and connecting stages; 2) physical sections of the railway network between node stations, stations for changing the technical equipment of sections, and the difference in the size of the movement of trains; 3) stations for the formation and destination of freight trains, stations for technical operations with freight trains, connecting their locomotive areas, and the work of locomotive cargo traffic crews; 4) stations for the formation and turnover of passenger trains, stations for technical operations with passenger trains connecting their locomotive areas, and the work of locomotive crews of passenger traffic; 5) destinations of a plan for the formation of freight trains; 6) destinations and schedule lines of freight trains of the fixed schedule; and 7) destinations and graphic lines of passenger trains.

Interconnected network mathematical models should, in the course of calculations, depict the dependencies of time and cost parameters on the loading of infrastructure elements and on the options for laying passenger trains. For this purpose, when preparing input information for optimization calculations, a multinetwork (several arcs between nodes A and B with different parameters and throughputs) should be generated, which will allow modeling various technological features of the movement of train flows and car flows.

3.2. Objective function

The objective function of maximizing the average daily financial result R is recorded in a general form, including all components that characterize the investment, operating expenses, income, and mutual payments of the participants in the transportation process. Depending on the structure of the railway transport for individual participants in the transportation process (infrastructure operators, freight and passenger carriers, and the operator of rolling stock), their components of the objective function take place. Using average values of indicators allows identifying the connection with the capacity and the permissible level of maneuverability of the railway polygon.

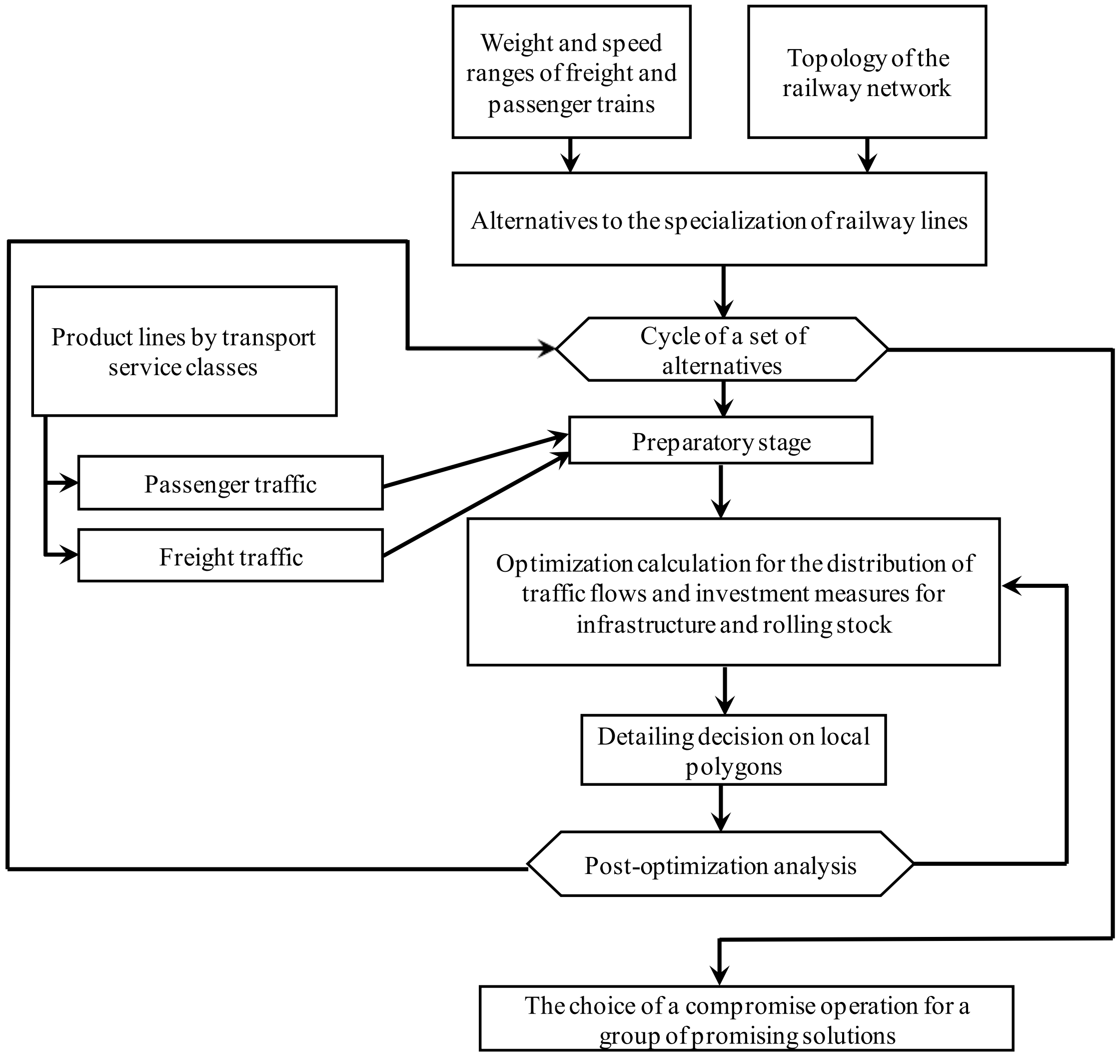

Fig. 3. The general sequence of the search for solving the problem of specialization of railway lines

$$R = \sum_i \sum_j D(X,Y)N_{ij} - \{\sum_k [E_1(X,N,Y) + K_1^*(X,N,Y)]_k + \sum_i \sum_j [E_2(X,N,Y) + \\ + E_3(X,N,Y)]N_{ij} + \sum_s K_2^*(X,N,Y)\} \pm [\sum_i \sum_j W_N(X,Y)N_{ij} + \sum_k W_k(X,Y) \to \max, \quad (2)$$

where i = 1,…, I – stations of departure of traffic flows; j = 1, …, J – stations for the assignment of traffic flows; k = 1, …, K – objects of railway infrastructure; s = 1, …, S – types of rolling stock; D – income rate; K^*_1 – the cost of changing the capacity of the infrastructure object, per day; K^*_2 – the cost of the new rolling stock, per day; W_N – mutual payments of participants in the transportation process related to traffic flows; and W_k – mutual payments of participants in the transportation process associated with infrastructure resources.

3.3. Controlled variables

In a general form, controlled variables characterize the following:

1) distribution of train flows and marshalling work (destinations of freight trains, attaching of wagons to the destination of freight trains, routes of freight trains on the railway network, norms of weight, and length of freight trains);

2) distribution of train flows in the passenger traffic (routes, number, and frequency of cruising of passenger trains by their categories and destinations);
3) technology of traction maintenance of freight and passenger traffic;
4) preparation for the work of passenger trains, maintenance and repair of locomotives and motorized rolling stock; and 5) investment measures.

Depending on the structure of the railway transport, separate sets of controlled variables take place for individual participants in the transportation process.

3.4. Restrictions

The objective function is subject to restrictions:

1) the indivisibility of traffic flows (the car flow of each destination of freight trains and each pair of passenger trains are indivisible and attached only to one of the possible routes);
2) infrastructure (loading of infrastructure elements should not exceed technically permissible levels);
3) resource (the required fleets of cars, locomotives and motor-trains should not exceed the permissible values);
4) logistic associated with permissible modes of movement of traffic flows along the railway network (providing specified levels of reliability - permissible time of travel, allowable deviations in departure and arrival time from specified values)

4. METHODS OF SOLUTION

The problem under consideration is combinatorial-optimization, the nature of which is due to the non-linearity and integer nature of a number of components of the objective function and constraints. It belongs to the class of NP-complete problems [4], for which there are no algorithms for strict optimization. The interrelation of the required indicators and the large dimension of the problem excludes the possibility of a complete search for the given polygon of the network for the distribution of the flow of passenger and freight trains. The choice of the algorithm for solving the problem should be based on an analysis of the properties of the objective function R and constraints.

Taking into account the analysis of the technological features of the problem, it is proposed to solve it by the method of sequential improvement of the original variant with the search for rational values for some variables at fixed others.

The optimization mode provides an approximate search for the basic solution (step-by-step distribution of traffic flows over the network of permissible assignments using the method [5]).

There are two principal methodological directions in solving the problem of the complex development of the railway network. The first direction involves the calculation of effective (efficiently implemented) distribution options and the organization of transport flows for the future, followed by the definition of investments in infrastructure and rolling stock, with a partial adjustment of individual options to reduce the total amount of construction and operation costs. The second direction involves the calculation of effective (efficiently implemented) distribution options and the organization of transport flows for the future with the direct inclusion of construction costs in the development of stations and lines, with the subsequent elaboration of the amount of all costs for the best variants.

In this study, the synthesis of both methodological directions is used in order to purposefully generate several solution variants with different operational advantages, conducting for specifying calculations for individual lines for the final choice of the solution.

Optimization calculations for the specialization of the railway network lines using the method [5] should provide for the direct account of construction costs - instead of penalties for exceeding the restrictions for infrastructure objects with development opportunities, values are entered $K^*_1(X, N, Y)$ and $K^*_2(X, N, Y)$. Thus, there will be an individual set of penalty functions, which work when infrastructural and resource constraints are exceeded, in each variant of the initial calculation data for optimizing the distribution of traffic flows.

Thus, a foreseeable number of effective alternatives is generated, for which it is possible to find a compromise operation using the method [6], which contains the original interactive algorithm for eliminating unacceptable solutions.

5. CONCLUSIONS

The specialization of railway lines is an extremely difficult technical and economic task. It is not enough to reduce railroad expenses by unifying train flows and simplifying operating modes, optimizing the life cycle of the infrastructure, and improving the use of resources. Restrictions on the solution are imposed not only by investment resources but also by the physical possibility of expanding the network objects. It is important, that loss of quality of transport services, speed and reliability of delivery of goods, level of passenger service, and, in general, loss of income of the railway transport should not be allowed. The growth of the functional vulnerability of the railway network in conditions of repair work, transport incidents, and other circumstances should not be allowed. Specialization should become the basis for the introduction of new transport products - regular and fast delivery of goods and multimodal transportation of goods and passengers.

The methodology for solving the problem of specialization of railway lines includes the following:

- a combination of network-wide optimization calculations with detailed studies that take into account the specificity of lines and nodes (see Fig. 3) and
- the adoption of resulting decisions based on a compromise of the criteria of the interacting participants in the transportation process.

References

1. Лапидус, Б.М. О научной поддержке реализации стратегических задач холдинга «РЖД». *Вестник научно-исследовательского института железнодорожного транспорта*. 2015. No. 1. P. 3-10. [In Russian: Lapidus, B. Scientific support to RZD Holding’s strategic tasks implementation. *«Bulletin of the Railway Research Institute» (Vestnik VNIIZHT)*].
2. Пехтерев, Ф.С. О концепции специализации железнодорожных линий на грузовые и пассажирские перевозки. *Бюллетень объединенного ученого совета ОАО «РЖД»*. 2013. No. 6. P. 27-36. [In Russian: Pekhterev, F.S. Concept of specialization in rail freight and passenger transport. *Bulletin of JSC «RZD» United Scientific Counsil*].
3. Михалевич, В.С. & Волкович, В.Л. *Вычислительные методы исследования и проектирования сложных систем.* Москва: Наука. 1982. 288 p. [In Russian: Mikhalevich, V.S. & Volkovich, V.L. *Computational methods for research and design of complex systems*. Moscow: Nauka].
4. Arjang, A. Assad. Modelling of rail networks: Toward a routing/makeup model. *Transportation Research Part B: Methodological*. 1980. Vol. 14. Nos. 1-2. P. 101-114.
5. Басевич, Т. & Новосельски, Л. *Процессы развития железнодорожного транспорта.* Москва: Транспорт. 1981. 129 p. [In Russian: Basevich, T. & Novoselski, L. *Processes of development of railway transport*. Moscow: Transport].
6. Wang, X. & Meng, Q. Discrete intermodal freight transportation network design with route choice behavior of intermodal operators. *Transportation Research Part B: Methodological.* 2017. Vol. 95. P. 76-104.
7. Petraska, A. & Jarasuniene, A. & Ciziuniene, K. Routing Methodology for Heavy-weight and Oversized Loads Carried by Rail Transport. *Procedia Engineering.* 2017. Vol. 178. P. 589-596.
8. Yaghini, M. & Nikoo, N. & Ahadi, H.R. An integer programming model for analyzing impacts of different train types on railway line capacity. *Transport*. 2014. Vol. 29. No. 1. P. 28-35.

9. Burdett, R.L. *Incorporating Complex Train Paths to an Analysis of Absolute Capacity.* School of Mathematical Sciences, Queensland University of Technology. Jan. 2015. Available at: https://www.researchgate.net/publication/286439001_Incorporating_Complex_Train_Paths_in_an_Analysis_of_Absolute_Capacity
10. Canca, D. & Barrena, E. & De-Los-Santos, A. & Luis, J. & Pineda, A. Setting lines frequency and capacity in dense railway rapid transit networks with simultaneous passenger assignment. *Transportation Research Part B: Methodological.* Nov. 2016. Vol. 93. Part A. P. 251-267.
11. A global vision for railway development*. International Union of Railways (UIC).* Paris, 2015. 44 p.
12. Gillen, D. & Hasheminia, H. Measuring reliability of transportation networks using snapshots of movements in the network – Analytical and empirical study. *Transportation Research Part B: Methodological*. Nov. 2016. Vol. 93. Part B. P. 808-824.
13. Crevier, B. & Cordeau, J.-F. & Savard, G. Integrated operations planning and revenue management for rail freight transportation. *Transportation Research Part B: Methodological.* Jan. 2012. Vol. 46. No. 1. P. 100-119.
14. Expósito-Izquierdo, C. & Melián-Batista, B. & Moreno-Vega, M. Pre-Marshalling Problem: Heuristic solution method and instances generator. *Expert Systems with Applications*. July 2012. Vol. 39. No. 9. P. 8337-8349.
15. Adlbrecht, J.A. & Hüttler, B. & Zazgornik, J. & Gronalt, M. The train marshalling by a single shunting engine problem. *Transportation Research Part C: Emerging Technologies.* Sept. 2015. Vol. 58. Part A. P. 56-72.
16. Milenković, M. & Bojović, N. A fuzzy random model for rail freight car fleet sizing problem. *Transportation Research Part C: Emerging Technologies.* August 2013. Vol. 33. P. 107-133.
17. Miloš S., Milenković & Nebojša J., Bojović & Švadlenka, L. & Melichar, V. A stochastic model predictive control to heterogeneous rail freight car fleet sizing problem. *Transportation Research Part E: Logistics and Transportation Review.* Oct. 2015. Vol. 82. P. 162-198.
18. Михалевич, В.С. & Кукса, А.И. *Методы последовательной оптимизации в дискретных сетевых задачах оптимального распределения ресурсов*. Москва: Наука. 1983. 208 p. [In Russian: Mikhalevich, V.S. & Kuksa, A.I. *Methods of sequential optimization in discrete network problems of optimal resource allocation*. Moscow: Nauka].
19. Батурин, А.П. & Бородин, А.Ф. & Панин, В.В. & Шумская, О.А. & Пояркова, М.А. Организация сетевых вагонопотоков в одногруппные поезда. *Железнодорожный транспорт.* 2005. No. 6. P. 17 – 24. [In Russian: Baturin, A.P. & Borodin, A.F. & Panin, V.V. & Shumskaya, O.A. & Poyarkova, M.A. Organization of network traffic flows to one-group trains. *Railway transport*].
20. Гогричиани, Г.В. & Ляшенко, А.Н. Выбор места расположения нефтяного терминала по комплексу противоречивых критериев. *Проектирование, сооружение и эксплуатация газонефтепроводов и газонефтехранилищ*. 2017. No. 2. P. 35-38. [In Russian: Gogrichiani, G.V. & Lyashenko, A.N. The choice of the location of the oil terminal on a set of conflicting criteria. *Design, construction and operation of gas and oil pipelines and gas and oil storage facilities*].

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