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Optimization of train routes based on neuro-fuzzy modeling and genetic algorithms

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Abstract

The article is devoted to the rationalization of the train routes on the railway network. It is proposed to improve the model of a decision support system based on the use of neuro-fuzzy modeling and a genetic algorithm intended for the formation of routes. Based on the improved model, it is possible to create an automated control system for the formation of optimal routes for passenger and freight trains. An optimization mathematical model of the railway network capacity control is also developed on the basis of the Ford-Fulkerson method. The model takes into account the limitations of the capacity of the sites of the landfill, the size of train flows (including speed) and the cost of following the train for each section. The implementation of the model will make it possible to more efficiently distribute train traffic on the railway network in the conditions of mass transportation of passengers and cargo.

Keywords: Railway network; Transportation; Dispatcher

1. Introduction

In modern conditions of functioning of the railways of Ukraine, insufficiently effective organizational and regulatory technologies are used as the basis for the organization of the transportation process, which limit the ability of the railway transport complex to flexibly respond to fluctuations in the demand of consumers in the transportation market. On this basis, in order to reduce transportation costs, it is necessary to use organizational

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technologies based on the concepts of flexible adaptive regulation of the transportation process of an operational and long-term nature in accordance with the principles of logistics. According to the Concept of the State Program for the Reform of Railway Transport of December 27, 2006 No. 651-p and the Industry Restructuring Program, one of the main directions of development of the organization of passenger traffic is the formation and further improvement of flexible technologies for managing the transportation process, is one of the ways to solve the problem of significant loss and use of resource-saving technologies.

2. Analysis of recent researches and publications

One of the important tasks of improving the transport system and the organization of transportation on the railways of Ukraine in modern conditions is the introduction of high-speed and speed traffic, it requires detailed analysis and use of world experience in high-speed and speed freight markets, searching for optimal directions and routes that will significantly accelerate the promotion trains on the railways of Ukraine.

The models proposed earlier in [1] for the formation of rational train routes can be effectively used to improve the system of organizing routes in both passenger and freight traffic of various messages. But for the mutual coordination of modeling processes and the possibility of their practical implementation, there is a need to include their work in a single integrated system of adaptive management. This can be done by creating a general model of organizing routes, the task of which will be to develop optimal routes based on the collection of reporting data on adjustment work at stations, and analyzing possible options for choosing the directions to follow. The result of such system will be the creation of the most economically and technologically feasible routes for trains, which will provide the passenger and freight transportation systems with flexibility and adaptability in changing working conditions, which are subject to constant fluctuations in demand. The development of such system has been proposed to implement in the form of a hybrid model based on a genetic algorithm and neuro-fuzzy modeling [1], which can be a functional basis for the further development of a decision support system (DSS).

According to [2, 3], the development of high-speed inter-regional transportation networks on the railways of developed countries of Europe is one of the top priorities in the provision of transport services in the field of passenger transportation, which, given the high-quality organization in terms of using modern transport technologies and infrastructure, has a huge financial success and attractiveness of demanding needs of modern passengers. In the field of freight traffic from the experience of modern railway networks in developed countries of the world [4] and in accordance with domestic development programs, the issues of speeding up the movement of freight trains are also violated very acutely. This is especially observed in the field of international transport for the promotion of foreign cars on the Ukrainian railways. To test the model and obtain results, it is advisable to use the methodology presented in [5].

3. Definition of the aim and objectives of research

The aim of research is forming an integrated model for determining the optimal routes for the accelerated movement of trains of various categories based on the mathematical apparatus of fuzzy logic, neural networks and the genetic algorithm. The objective of research is a mutual functional combination of model structures for obtaining an integrated model, which may in the future be the basis of a decision support system (DSS).

4. Construction of the base railway landfill graph

Simulation of routes for accelerated trains consists in finding the best options for following them within a certain network, the model of which is represented as a weighted graph $G(V, E)$, in which V – a set of vertices, which are junction stations, and E – a set of edges, representing the areas between stations. Edge weights are genes h_{ij}^{k} that model certain railway sections (see Fig. 1).

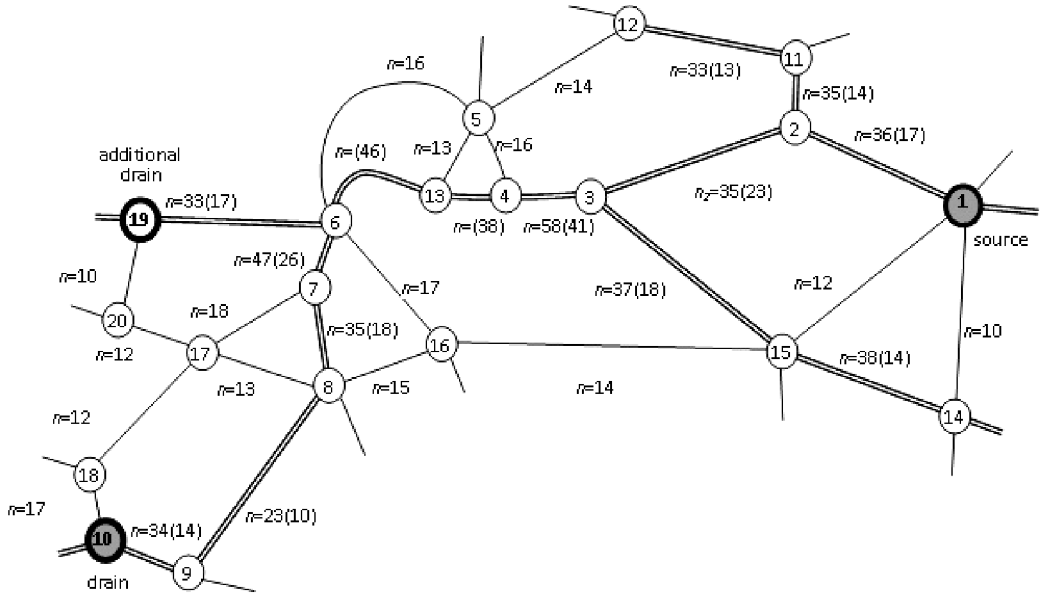

Fig. 1. Weighted graph G (V, E) of the railway network.

5. Formation of neuro-fuzzy model for optimizing train routes

The task of finding the optimal route for a train to travel within a certain network is finding a certain set of sections of a train's way from *i*-th departure stations to *j*-th destination stations, the successive passage of which by train forms a common route, compared to other options, more efficient with respect to optimization criteria for provided that stations *i* and *j* can be expediently used to stop the relevant categories of trains in certain directions. Therefore, as a chromosome, it is advisable to present a certain route consisting of a specific set of genes – sections *i-j* of the railway junction, where each gene respectively models a section of the sequence between a certain pair of stations *i-j*. Chromosome will look like

$$H = \sum_{i,j=1}^{v} h_{ij} \in \left\{ h_{ij}^{1}, h_{ij}^{2}, \ldots h_{ij}^{k}, h_{ij}^{k+1}, \ldots h_{ij}^{m} \right\} \quad h_{ij}^{k} = \begin{cases} 1- \text{ is possible} \\ 0- \text{ is impossible} \end{cases} \tag{1}$$

where:

- v – the number of stations in the simulated node
- h_{ij}^{k} – gene, which models certain variants of following from the station of departure i to the station of destination j and takes the value 1 or 0
- m – the total number of genes in a particular route
- k – specific gene route from the total population m, $k \in m$

The initial stage of solving the problem of finding the optimal combination in the model of a genetic algorithm is the formation of the initial population, carried out by randomly searching and placing the genes and their values in a given set of chromosomes with their representation as a twinned sequence of a fixed length. So, the primary genotype of the model will be a set of chromosomes $H \in \left\{ h_{ij}^{1}, h_{ij}^{2}, \ldots h_{ij}^{k} \right\}$, each of which models one specific route. In this case, the genes in each chromosome are arranged differently, simulating a different sequence of direction sections. Thus, in the combination of the genes of each chromosome, a different route is presented, the genes of which are arranged in a different sequence.

Evaluation of chromosome fitness in a population or selection of the best route options is carried out for each chromosome of the original population using efficiency criteria, which form the basis of the fitness function. The task of finding the optimal accelerated route is determination of the option with the best value for the fitness function, namely, the minimum time spent, which indicates the need to direct the fitness function task to the search for a minimum.

However, it is necessary to take into account some features of the formation of routes in terms of using a genetic algorithm, which is the basis of the system of restrictions:

- The final arrival station *j* in the last gene h_{ij}^{m} of a certain chromosome route has to coincide with the initial departure station *i* in the first gene h_{ij}^{1} of the next chromosome route; it ensures that the routes are closed, which is especially important for passenger traffic
- Within the limits of a certain chromosome route, the departure station *i* of each next gene h_{ij}^{k+1} has to coincide with the arrival station *j* of each previous gene h_{ij}^{k} ; it ensures a sequence of sections in the route
- The total length of sections following the selected genes of each chromosome route $\sum_{i,j=1}^{n} l_{ij}^{k} h_{ij}^{k}$ should not exceed the maximum distance of movement between adjacent technical service operations of rolling stock $L_{\max}^{SO-2}$; it ensures timely execution of technical operations
- The total travel time for *i-j* sections of selected genes according to the chromosome route $\sum_{i,j=1}^{n} t_{ij}^{k} h_{ij}^{k}$ must not exceed the duration of following the established train schedule for the locomotive crew change point $T_{\max}^{lc}$

It takes into account the duration of the work of the locomotive crews.

The determined criteria form a system of restrictions that must be incorporated into the fitness function and requires its structuring. These conditions are the basis for limiting the totality of the simulated routes through checking their implementation and screening out those that did not pass, that is, the least adapted chromosomes.

$$FF1(H)=\begin{cases}\min, \text{ if } i\in h_{ij}^{1}=j\in h_{ij}^{1+m} \cup j\in h_{ij}^{k}=i\in h_{ij}^{k+1} \text{ if } h_{ij}^{k}=1\\ \max, \text{ in another case}\end{cases}, \tag{2}$$

$$FF2(H)=\begin{cases}\min, \text{ if } \sum_{i,j=1}^{n} l_{ij}^{k}h_{ij}^{k}\le L_{\max}^{TO-2} \cup \sum_{i,j=1}^{n} t_{ij}^{k}h_{ij}^{k}\le T_{\max}^{лб} \text{ if } h_{ij}^{k}=1\\ \max, \text{ in another case}\end{cases}. \tag{3}$$

The general task of the simulation is to find the optimal route from the set of the primary genotype, which fully corresponds to conditions (2) and (3). The criterion for the search is the minimum total cost of following the route laid down in the chromosome, consisting of the sum of the costs of movement for each section in accordance with the selected genes

$$FF3(H)=\min\sum_{i,j=1}^{n} t_{ij}^{k}h_{ij}^{k}, \tag{4}$$

where t_{ij}^{k} – the level of time spent on movement according to the gene h_{ij}^{k} , which is determined by the time spent on processing at the departure station t_{pr}^{n} and the time spent on movement between stations t_{ij}^{n} over a certain area n.

$$t_{ij}^{k} = x_{ij}^{n}\cdot\left(t_{обр}^{n}+t_{ij}^{n}\right), \tag{5}$$

where x_{ij}^{n} – parameter that determines the level of the train departure to the *n*-th site according to the simulation results according to [1] and is defined as

$$x_{ij}^{n} = \frac{100\% - X}{100\%}, \tag{6}$$

where X in accordance with [1] corresponds to the task of determining the expediency level of departure of an interregional train to the *n*-th direction.

$$X = \left(\Delta N_{ij}, t_{ij}\right) \to D \in \left\{d_1, d_2, \ldots, d_k\right\}, \tag{7}$$

where d_k – feasibility of a particular appointment in %.

As input parameters of a fuzzy model, let's consider two fuzzy variables: $N_1 = \Delta N_{ij}$ = "Capacity reserve of some sections *ij*" (L – low, M – medium, H - high), $N_2 = t_{ij}$ = "Time spent on passing some sections *ij*" (LO – lower than optimal, O – optimal, HO – higher than optimal).

The choice of the optimal initial value d_k based on the comparison of input parameters is carried out on the basis of rules in the form of fuzzy conditional judgments of the "If ... then" type, where the first part of the rule contains a set of conditions, and the second is a consequence of the conclusion. The basis for the formation of fuzzy rules is expert judgments on the choice of options for actions with a certain ratio of input parameters. Therefore, according to the aforementioned approach, a system of fuzzy rules [1] was developed on the basis of expert analysis and the development of appropriate practical solutions for choosing the optimal route option.

The calculation of the value of the parameter X is carried out according to the results of the neuro-fuzzy model, the structure of which is shown in Fig. 2.

For learning a neuro-fuzzy network, a training sample of 90 experimental data was created in the form of <input (ΔN_{ij}, t_{ij}) - output (*d*)>. The minimum learning error is 0.35221% and is achieved in the region of the 84-th iteration of the algorithm. After the 84-th iteration, the error becomes constant, which indicates that the model loses generalization properties.

A test of the model adequacy is conducting its learning on a test sample. Fig. 3 shows the results of testing the model after learning as the degree of accuracy of hitting the output value in the region of a particular solution.

Analysis of the test results indicates a fairly high level of accuracy of the model, the minimum error level of which does not exceed 0.35%, and the total – 5%. High accuracy of work is saved at about 42 iterations, after which there is a loss of accuracy in certain solutions, which requires further learning of the model on new data.

Thus, the choice of the best route is carried out through checking all the options to fulfill the three specified conditions (2), (3), (4). So, the fitness function should consist of three parts, and a general solution containing the sum of the values for each condition is sent to find the smallest value.

$$FF(H) = \left(FF1(H) + FF2(H) + FF3(H)\right) \Rightarrow \min \tag{8}$$

If the minimum value of the function is obtained, the stop of the algorithm can be implemented after reaching this value, it will mean finding the optimal solution. Finding at this stage the optimal isolation, which corresponds to the lowest costs for movement along a certain route, is the completion of the genetic algorithm model. If, in the aggregate of the obtained solutions, no one corresponds to the optimal value, the next stage of modeling is the selection of chromosomes, after which genetic operators are applied to the chromosomes selected by selection. The presented cycle of operations is repeated until a chromosome with the best value of the fitness function is found.

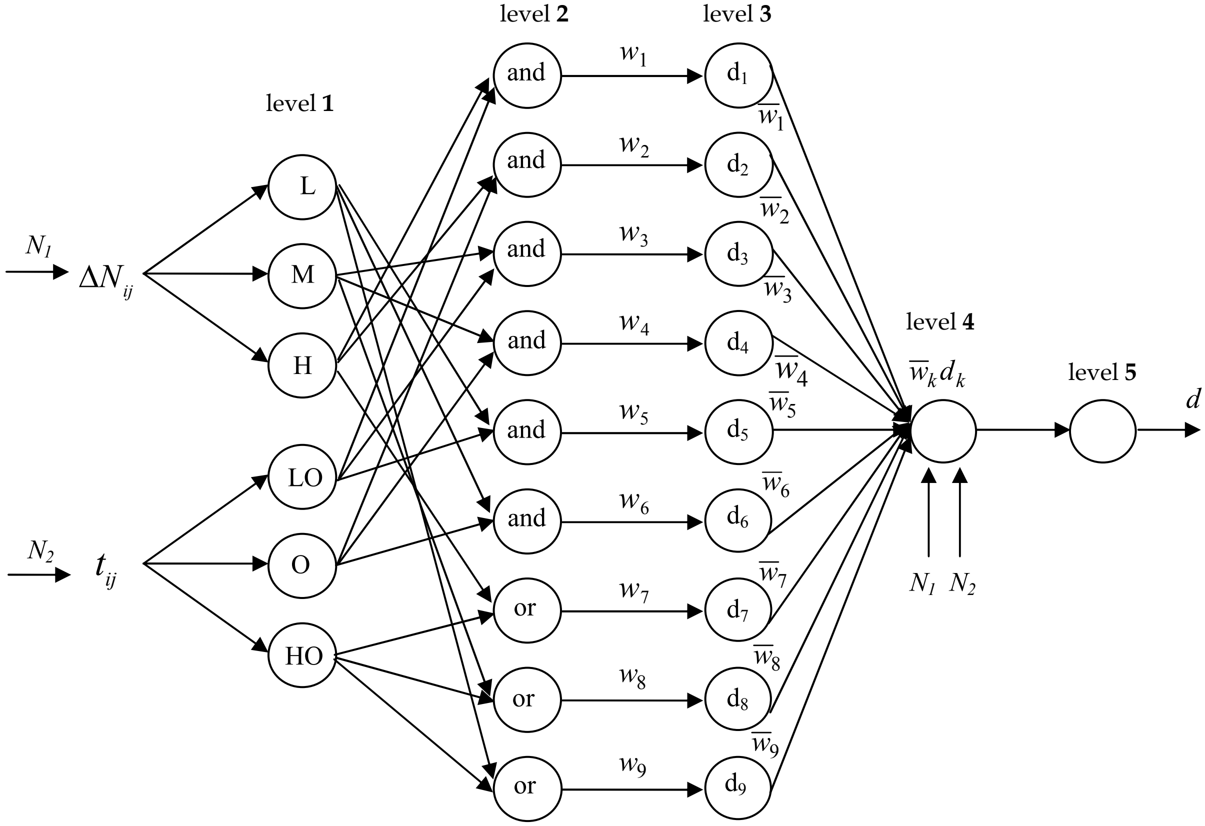

Fig. 2. Neuro-fuzzy structure of the ANFIS network.

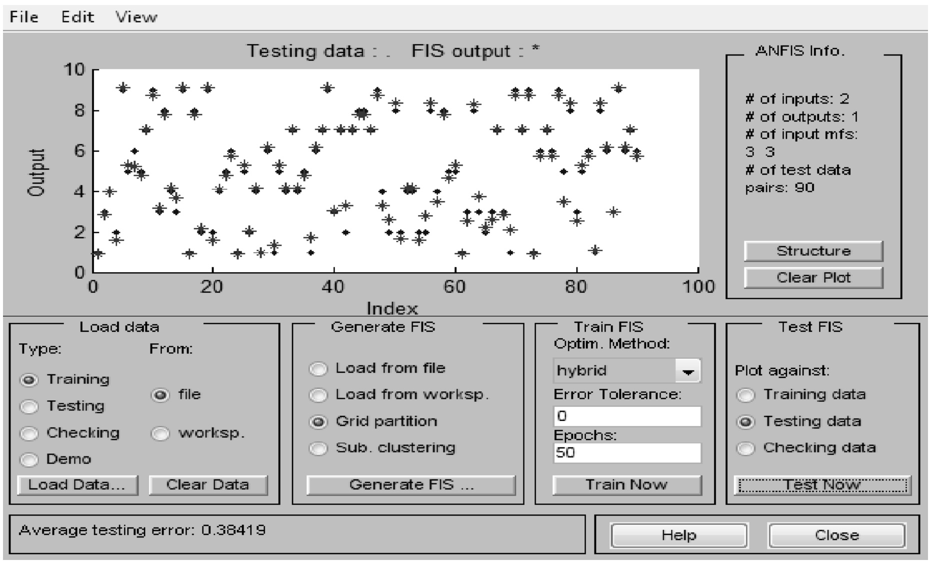

Fig. 3. Results of testing the neuro-fuzzy model.

6. Determination of routes of trains in the conditions of mass movement of passenger trains and capacity limitations

To verify the adequacy of the proposed model for finding optimal routes based on the use of a genetic algorithm and neuro-fuzzy modeling, let's use an optimization mathematical model for controlling the capacity of a railway network based on an open-type transport problem with constraints and the Ford-Fulkerson method [5]. To implement the simulation, let's use the basic railroad landfill scheme in the form of a weighted graph *G (V, E)*, which is shown in Fig. 1. During the verification of the model, the operational optimization problem was solved by means of train flows, which takes into account the operational changes in the topological structure of the network at the closure of the main tracks, as well as the cost of following trains for each section of the railway test site.

Each of the starting points $A_i(i=1, \ldots, m)$ of the base polygon must send p_i trains. Each of the departure points $B_j(j=1, \ldots, n)$ must take w_j trains. The maximum number of trains can skip each section per day is given by the variable n. The capacity of the double-track section is given in brackets in the event that one track is closed. Let's formulate a problem to determine the optimal distribution of a direct flow on the base railway range in a formal form in terms of the mathematical apparatus of graph theory. Scientific studies were carried out using mathematical methods of directional enumeration of options and Ford-Fulkerson [5].

The graph *G (V, E)* with the capacity $c(u, v)$ of its cut and the flow $f(u,v)$ for edges from u to v. It is necessary to find the maximum flow from the source s to the drain t. At each step of this method, the same conditions apply for each flow.

$$f(u,v) \le c(u,v), \tag{9}$$

that is, the flow from u to v must not exceed the capacity of the edges;

$$f(u,v) = -f(u,v); \tag{10}$$

$$\sum_{v} f(u,v) = 0 \Leftrightarrow f_{in}(u) = f_{out}(u) \tag{11}$$

for all nodes u except s and t. The flow does not change when passing through the node.

Thus, we have a weighted graph G with a capacity c, a source s, and a drain t. It is necessary to obtain the optimal distribution of the maximum flow f from s to t. While the path p from s to t, such that $c_f(u, v) > 0$ for all edges $u,v) \in p$, let's define $c_f(p) = \min \{ c_f(u, v) \mid (u, v) \in p\}$, and for each edge $(u, v) \in p$ the conditions should be true

$$f(u,v) \leftarrow f(u,v) + c_f(p); \tag{12}$$

$$f(v,u) \leftarrow f(v,u) + c_f(p). \tag{13}$$

Consequently, when entering station 1, which is the source of the graph, from 1 to 12 trains per shift (12 hours), they are skipped along the shortest path 1–2–3–4–5–6–7–8–9–10. The capacity of section 2-3 is also used for other train flows, therefore, taking into account the maximum use of the locomotive fleet and the intensive passenger traffic. It amounts to 12 trains. As a result, if it is necessary to pass from the 13-th train, it is advisable to use the most economically efficient route, bypassing section 2-3, namely 1–15–3–4–5–6–7–8–9–10, as shown in Table 1.

With an increase in flow out to 14 or more trains, section 8-9 becomes limiting, which can only be missed by 13 trains of a given direction per shift. Therefore, trains starting from the 14-th are advisable bypassing section 8-9 on route 1–15–3–4–5–6–7–17–18–10. In the same way, the necessary and available abilities of the sites are compared and the distribution of 1–10 outgoing traffic along various rational routes is constructed. When carrying out repair work on a double track section with the closure of one route, the throughput of the entire section is sharply reduced.

In this work, the distribution of train flow in case of closing one track of the section 2-3 is simulated. At the same time, the capacity is reduced to one train per shift. The distribution order of the train flows for this case is given in Table 2. As can be seen, only one train can be missed for the effective 1–2–3–4–5–6–7–8–9–10 route. Starting from the second train, it is advisable to bypass section 2-3 along the route 1–15–3–4–5–6–7–8–9–10. In this case, single-track section 1–15 is now becoming the limiting one, which can miss only seven trains per shift. Therefore, if there are more than 8 trains, it is necessary to pass on the third option – along the route 1–2–11–12–5–6–7–8–9–10 etc.

Table 1. Distribution of train flows along route 1-10.

Possible sizes of the train flows 1-10, trains shift	The main and additional routes of trains flows	Limiting sections
1 – 12	1–2–3–4–5–6–7–8–9–10	2–3
13	1–15–3–4–5–6–7–8–9–10	2–3, 8–9
14–16	1–15–3–4–5–6–7–17–18–10	2–3, 8–9, 5–6
17 – 19	1–15–16–8–9–10	2–3, 8–9, 5–6, 1–15
20–21	1–2–11–12–5–13–6–7–17—18–10	2–3, 8–9, 5–6, 1–15, 17–18
21 – 25	1–2–11–12–5–13–6–19	2–3, 8–9, 5–6, 1–15, 17–18, 12–5

Table 2. Distribution of train flows on route 1–10 when closing one track in two-track section 2-3.

Possible sizes of the train flows 1-10, trains shift	The main and additional routes of trains flows	Limiting sections
1	1–2–3–4–5–6–7–8–9–10	2–3
2–8	1–15–3–4–5–6–7–8–9–10	2–3, 1–15
9–13	1–2–11–12–5–6–7–8–9–10	2–3, 1–15, 8–9
14	1–2–11–12–5–6–7–17–18–10	2–3, 1–15, 8–9, 12–5
15–16	1–14–15–3–4–5–6–7–17–18–10	2–3, 1–15, 8–9, 12–5, 5–6
16–18	1–14–15–16–8–17–18–10	2–3, 1–15, 8–9, 12–5, 5–6, 1–14

According to Table 1 and Table 2, it is advisable to issue output to dispatcher personnel who can plan passing the increased train flow through the sections taking into account this distribution.

7. Conclusion

The implementation of a decision support system based on the proposed model in the railroad traffic management service will automate the process of forming routes and improve existing train schedules. In terms of the use of new models of high-speed rolling stock in the system of passenger and freight traffic and the need to accelerate progress, this will optimize operating costs, increase revenues and implement a better system of traffic organization.

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