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ORIGINAL ARTICLE

Algorithm for the approximate scheduling of network section's track maintenance in railway traffic control problem

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Abstract

Algorithmic and contributory assistance in resolving railway traffic control problems is being developed. It is founded on presenting practical issues in optimizing declarations using linear programming implements. A novel challenge of determining a pathway control a time interval during which some sectors of the railway network are blocked for reparation work is added to the previously proposed models. Applicable statements, aimed at the synchronized examination for pathway control and a train timetable for a detailed portion of the railway network A mathematical model and an optimized strategy are offered as solutions. The creative situation is simplified to a mixed integer linear problem. To explain potential computing challenges in resolving an issue, a method for obtaining an estimate is planned. It would be founded on creating a rudimentary movement timetable and its consequent revision to the reason for the necessity for railway control. Two algorithms are implemented to get an approximate solution. A basic and adapted train schedule is formed in stages of groupings of trains connected by another origin and target terminals in the first. Steps were performed single train once a time as per the time of preparation for leaving in the second. A mathematical experimentation's findings are provided.

1. Introduction

The assignment task is one of the urgent tasks of railway transport management. The mission of finding the time intermission in which several sectors of the railway network are locked for reparation work. Ideally, it should not affect the traffic schedule, i.e., when the areas to be repaired are free of traffic. However, this is only sometimes possible due to the intensity of train traffic. At the same time, an arbitrary choice of the time interval for maintenance can lead to delays and cancellation of trains. In this regard, the task arises of finding the optimal time interval for the appointment from the point of view of various criteria. Among the works devoted to the study of this problem, we highlight [1, 2]. In [3], the assignment task was considered on a particular segment of the railway network, and in one station. In [4], the problem was solved simultaneously with the search for the train timetable. In [5], adjusting some of the original schedules and embedding them into them was proposed. In [6], the movement of trains was proposed to be approved along some predetermined routes. The assignment problem in [7] was expressed as a mixed integer linear programming problem. This article presents a modification of the results [8]; it continues the development of algorithmic and instrumental sustenance for disentangling railway transportation management problems founded on the formalization of practical issues in mathematical models

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optimized by linear programming. Developing this technique, the paper uses the mathematical model proposed in [9, 10]. It improves movement along the multigraph of the railway network, as well as the universal optimality criterion presented in [11] for the formation of a timetable. Based on the model and several restrictions devoted to considering the need for maintenance [12], a new task of assigning maintenance on sections of the railway network has been set. Due to computational difficulties in finding the optimal solution to the resulting problem, two algorithms for finding an approximate solution are proposed. These algorithms are compared using a meaningful example.

2. Basic designations and assumptions

Contemplate a railway network exemplified by a directionless multigraph G= 〈V,e〉 , where V is the set of nodes (positions anywhere the railway network branches, whose numeral of arriving paths is not equivalent to the integer of leaving pathways, sorting or final); E is the set of edges (paths) linking the data vertexes. Let the number of nodes |V | = m. Having numbered the vertices of graph G, we make up the set of indices, $V' = \{1,2, \dots, M\}$ both component of which defines an apex of graph G. A natural constraint M≥ 2 is assumed.

Let there be (I) trains. For each i train, $i = \overline{1, I}$, are given: the index of the departure vertex $v_i^{\text{send}} \in V'$; the index of the destination vertex $v_i^{\text{arrival}} \in V'$; the time of readiness for departure t_i^{send} which is premeditated as the number of minutes since a certain set point of reference; the supreme time di through which the train is allowable to be at the end of leaving from the moment of willingness; travel time Ti, i.e.,the maximum time, through which the train is allowable to stay on the railway network, calculated in minutes. The motion of trains along the stretches (among the peaks) of the railway network container only be conceded out at specific intermissions. To designate such gaps, the concept of a set of conflict-free "sub-platforms" is used. This is a subset of all the "sub-platforms", which is conflict-free in the sense that there cannot be two "sub-platforms" in this set when using which two trains will collide. For example, such a set was used in[13, 14] when studying the task of assigning locomotives.

Further, this set is denoted by Z and is considered to be given a priori, i.e., it is an input parameter in the problem under consideration. Let the number of elements $|Z| = K'$and they are numbered from 1 to K. Each element $z_k \in Z$, $k = \overline{1, K}$, is a five $z_k = (v_k^{\text{start}}, v_k^{\text{end}}, n_k, t_k^{\text{start}}, t_k^{\text{end}})$, where $v_k^{\text{start}}, v_k^{\text{end}} \in V'$are the directories of next to vertices in graph G of the beginning and end of the movement along the "sub-platforms"; n_k the numeral of the pathway attaching these vertices; t_k^{start} also $t_k^{\text{end}}$is the start and end time of the movement. The movement of the train may also be subject to restrictions related to parking at intermediate stations. For example, at some stations, there should be an alteration of trains, uncoupling/hitching of wagons, and several positions, on the contrary, should be passed by without stopping. Consequently, we will present the minimum and maximum conceivable period of parking at work with the vertex indication v_k^{end} afterward consuming the "sub-platforms" through the numeral k of the train with the numeral $i: t_{i,k}^{\text{st.min}}$ and $i: t_{i,k}^{\text{st.max}}$. For $T_{\max}$. we denote the duration of the movement period: for instance, if the timetable is made for the daytime, then For $T_{\max}$= 1441 minutes. Let Δ be the minimum duration of THAT, and t_1^0 is the time not earlier than which THAT can begin, and t_1^0end. By $Z' \subset \{1, \dots, K\}$we denote the set of "sub-platforms" containing the stages on which the work should be carried out.

3. Calculated model of train traffic on the graph of the railway network

Let's set the task of finding the travel time of those, as mentioned earlier, I train over the railway network specified through the multigraph G, founded on the set of "sub-platforms" Z. The route of the i_{th}train is the sequence of vertices intersected by it. We introduce variables $\delta_{i,j,k}$characterizing the use by the i_{th} train of a "sub-platforms" with the number k at the j_{th} phase of the road (when moving from the $j_{th}$to $j + 1_{th}$in the order of the vertex) , $i = \overline{1, I}, j = \overline{1, J+1}$, $k = \overline{1, K}$. Here J is a preset parameter - the number of "real" stages at which movement from station to station occurs, stage J+1 is technicall; there is no movement on it, and it is needed for the correct assignment of the conditions of arrival at the designated point in the model. The variable $\delta_{i,j,k}$ is equal to 1 if the i_{th} train on the j_{stage} involves "sub-platforms" with a number, otherwise 0. Let's use the mathematical model of movement lengthways multigraph of the railway network from [15], given by the following restrictions on binary variables $\delta_{i,j,k}$:

for $i = \overline{1, I}$, $k = \overline{1, K}, m = \overline{1, M}$:

$$\sum_{i=1}^{I} \sum_{j=1}^{J+1} \delta_{i,j,k} \le 1, \sum_{k=1}^{K} \delta_{i,j,k} = 1, \sum_{k=1}^{K} \delta_{i,j,k} v_k^{\text{start}} = v_i^{\text{send}}, t_i^{\text{send}} \le \sum_{k=1}^{K} \delta_{i,j,k} t_k^{\text{start}} \le t_i^{\text{send}} + d_i, \sum_{j=1}^{J+1} \sum_{k: v_k^{\text{start}} = m, 1 \le k \le K} \delta_{i,j,k} \le 1; \quad (1)$$

for $j = \overline{1, J-1}$

$$\sum_{k=1}^{K} \delta_{i,j,k} v_k^{\text{end}} \le \sum_{k=1}^{K} \delta_{i,j+1,k} k^{\text{start}} + \left(1 - \sum_{k=1}^{K} \delta_{i,j+1,k}\right) M^3, \sum_{k=1}^{K} \delta_{i,j,k} v_k^{\text{end}} \ge \sum_{k=1}^{K} \delta_{i,j+1,k} k^{\text{start}} - \left(1 - \sum_{k=1}^{K} \delta_{i,j+1,k}\right) M, \sum_{k=1}^{K} \delta_{i,j,k} \left(t_k^{end} + t_{i,k}^{\text{st.min}}\right) \le \sum_{k=1}^{K} \delta_{i,j+1,k} \left(t_k^{\text{start}}\right) + 2\left(1 - \sum_{k=1}^{K} \delta_{i,j+1,k}\right) T_{\max}, \sum_{k=1}^{K} \delta_{i,j,k} \left(t_k^{end} + t_{i,k}^{\text{st.min}}\right) \ge \sum_{k=1}^{K} \delta_{i,j+1,k} \left(t_k^{\text{start}}\right); \quad (2)$$

for $i = \overline{1, J}$

$$\sum_{k=1}^{K} \delta_{i,j,k} t_k^{\text{end}} - \sum_{k=1}^{K} \delta_{i,j,k} t_k^{\text{start}} \le T_i, \sum_{k=1}^{K} \delta_{i,j,k} v_k^{\text{end}} \ge \left(\sum_{k=1}^{K} \delta_{i,j,k} - \delta_{i,j+1,k}\right) v_i^{\text{arrival}}, \sum_{i=1}^{I} \sum_{k=1}^{K} \delta_{i,j+1,k} =$$

$0, \sum_{k=1}^{K} \delta_{i,j,k} v_k^{\text{end}} \leq \left(1 + \sum_{k=1}^{K} \delta_{i,j+1,k} - \delta_{i,j,k}\right) M + \left(\sum_{k=1}^{K} \delta_{i,j,k} - \delta_{i,j+1,k}\right) v_i^{\text{arrival}}$ (3)

Restrictions (1)–(3), in particular, consider trains can depart only from the corresponding departure vertices; movement is possible only along adjacent vertices of the multigraph G; trains cannot depart from intermediate stations on the route before arrival. These ways do not contain cycles are used. A detailed description of the presented limitations can be found in [16].

4. Additional restrictions for the purpose of the technological window

To exclude the possibility of movement along the "sub-platforms" associated with the arcs of the multigraph G to be repaired, we will use the restrictions from [17, 18]. To do this, we introduce auxiliary binary variables $\Upsilon_{k'}$& $æ_{k'} k' \in Z'$, and constraints

$\Upsilon_{k'} t_{k'}^{\text{end}} \leq t_1, t_1 \leq æ_{k'} t_{k'}^{\text{start}} + (1 - æ_{k'}) T_{\max}, \delta_{i,j,k'} \leq æ_{k'} + \Upsilon_{k'}, i = \overline{1,I}, j = \overline{1,J}, k' \in Z';$ (4)

$t_2 - t_1 \geq \Delta, t_1^0 \leq t_1, t_2 \leq t_2^0.$ (5)

Constraints (4) make it possible to exclude from the movement "sub-platforms" that fall into the. The constraints (5) guarantee will be no less than the specified duration Δ, it will start no earlier than t_1^0 and end no later than t_2^0 .

5. Selection criteria

Using the criterion from [19], we obtain the optimization problem

$c_1 \sum_{i=1}^{I} \sum_{j=1}^{J+1} \sum_{k=1}^{K} \delta_{i,j,k} (t_k^{\text{end}} - t_k^{\text{start}}) + c_2 \sum_{i=1}^{I} \sum_{j=1}^{J+1} \widehat{T_{i,J}} + c_3 \left(\sum_{i=1}^{I} \sum_{j=1}^{J+1} \delta_{i,j,k} t_k^{\text{start}} - \sum_{i=1}^{I} t_i^{\text{send}}\right) \to min$ (6)

Under constraints (1)–(5) and

$\widehat{T_{i,J}} \geq \sum_{k=1}^{K} \delta_{i,j+1} t_k^{\text{start}} - \sum_{k=1}^{K} \delta_{i,j} t_k^{\text{end}}, i = \overline{1,I}, i = \overline{1,J}.$ (7)

Criterion (6) is a convolution of three criteria, the contribution of each is regulated by the choice of positive constants c_1 , c_2 and c_3 . The first term is responsible for the total time in motion, the second for the total duration of stops at intermediate stations, the third for the total duration of stops at departure stations. Through $\widehat{T_{i,J}}$ notes the parking time of the i_{th} train at the $(j+1)_{th}$ station in the route, $\widehat{T_{i,J}} = 0$. The minimum is taken by the variables $t_1, t_2, \delta_{i,j,k}, \widehat{T_{i,J}} \geq 0, \Upsilon_{k'}, æ_{k'}, i = \overline{1,I}, i = \overline{1,J+1}, k = \overline{1,K}, k' \in Z'$.

6. Algorithm for finding an approximate/initial solution

As it was noted in[20], the solution to the problem (6), even with constraints (1)–(3) and (7), is very trying; restrictions (4), and (5) make the problem even more complicated. Therefore, the following sequence of actions is proposed to find an approximate solution. First, it is necessary to build a timetable under the assumption that there is no maintenance. Next, there is selected so that the minimum number of trains falls into it (a similar technique is used to assign at the station in [21]). Next, you need to exclude the "sub-platforms" that fall into the, including those that violate the restriction (4) and re-build the timetable for all trains. So, let some train schedules throughout the railway network. Denote by $Z_i \subset \{1, \ldots, K\}$ the set of numbers of "sub-platforms" used when traveling by the i_{th} train. Next, we will form a group of train numbers $\overline{\mathfrak{I}} = \{i: Z_i \cap Z' \neq \emptyset$. If the set $\mathfrak{I}$ is empty, then you can assign that of any duration within the planning horizon. If the set $\overline{\mathfrak{I}}$ is non-empty, you need to solve the problem of minimizing the number of trains that fall (in time and place) into the. To do this, we will introduce additional variables $\tilde{\delta}_p$, equal to 0 if the train route with the number p falls into that, and 1 in the reverse situation. We likewise present new variables $\tilde{\delta}_p^{k_p}$, equal to 0 if the intersection of segments $[t_1, t_2]$ and $[t_{k_p}^{\text{start}}, t_{k_p}^{\text{end}}]$ consists of a maximum of one point, and 1 otherwise, $p \in \overline{\mathfrak{I}}, k_p \in Z_p \cap Z'$. The equality of 1 variable $\tilde{\delta}_p^{k_p}$ means that the "sub-platforms" with the number $k_p$used by the p_{th}train will be unavailable due to that; for the equality of 0 variable $\tilde{\delta}_p^{k_p}$, the condition $t_1 \geq t_{k_p}^{\text{end}}$ or $t_2 \leq t_{k_p}^{\text{start}}$ must be fulfilled. Therefore, we will introduce additional variables $a_p^{k_p}$and $\beta_p^{k_p}$:

$$a_p^{k_p} = \begin{cases} 0, & \text{if } t_1 \geq t_{k_p}^{\text{end}}; \\ 1 & \text{otherwise;} \end{cases}$$
$$\beta_p^{k_p} = \begin{cases} 0, & \text{if } t_1 \geq t_{k_p}^{\text{end}}; \\ 1 & \text{otherwise;} \end{cases}$$

So $\tilde{\delta}_p^{k_p} = 1$ only when $a_p^{k_p} = \beta_p^{k_p} = 1$. Using the entered variables, we get the folloing problem:

$\sum_p \tilde{\delta}_p \to min, \tilde{\delta}_p \geq \frac{1}{K} \left(\sum_{k_p} \tilde{\delta}_p^{k_p}\right), p \in \overline{\mathfrak{I}}, k_p \in Z_p \cap Z', t_1 \geq \left(1 - a_p^{k_p}\right) t_{k_p}^{\text{end}}, t_2 \leq \left(1 - \beta_p^{k_p}\right) t_{k_p}^{\text{start}} + \beta_p^{k_p} T_{\max}, \tilde{\delta}_p^{k_p} \geq a_p^{k_p} + \beta_p^{k_p} - 1, t_2 - t_1 \geq \Delta, t_1^0 \leq t_1, t_2^0 \leq t_2$. (8)

The minimum in (8) is taken by the variables t1$t_1, t_2, \tilde{\delta}_p, \tilde{\delta}_p^{k_p}, \alpha_p^{k_p}, \beta_p^{k_p}$. Note that constraint (5) is included in problem (8). If the optimal value of the criterion $\sum_{p \in \overline{\mathfrak{I}}} \tilde{\delta}_p$ minimized in (8) is 0, then there is no need to rebuild the existing schedule. If it is greater than 0, then you need to rebuild the train schedule taking into account the "sub-platforms" that fall into the, i.e. do not use these "sub-platforms" when searching for the schedule. As a result, we get the following algorithm.

Step 1. Many rooms trains is divided into S disjoint subsets $\Im_s$, i. e. $\{1,\ldots,I\} = \cup_{s=1}^{S} \Im_s, and\ \forall\ s_1 \neq s_2, \Im_{s1} \cap \Im_{s2} = \emptyset$.

Step 2. The parameter $S = 1$ is initialized. The set $\aleph_0 = \emptyset$ is formed.

Step 3. The problem of minimizing criterion (6) with constraints (1)–(3) and (7) is solved with respect to the set of trains $\Im_s$, i. e.

$$c_1 \sum_{i\in\Im} \sum_{j=1}^{J+1} \sum_{k=1}^{K} \delta_{i,j,k} (t_k^{\text{end}} - t_k^{\text{start}}) + c_2 \sum_{i\in\Im} \sum_{j=1}^{J+1} \widehat{T_{\iota,J}} + c_3\left(\sum_{i\in\Im} \sum_{k=1}^{K} \delta_{i,1,k}\ t_k^{\text{start}} - \sum_{i=1}^{I} t_k^{\text{send}}\right) \to min \quad (9)$$

under the additional condition $\delta_{i,j,k} = 0, i \in \Im_s, j = \overline{1, J+1}, k \in \cup_{p=0}^{s-1} \aleph_{\text{p}}$. (10)

If there is a solution to this problem, then a set of numbers of "sub-platforms" $\aleph_s$ occupied thru trains by numbers as of $\Im_s$ is formed, then the transition to step 4 is performed. Otherwise, the search for an approximate solution is completed unsuccessfully.

Step 4. If $s = S$, then the transition to step 5 is performed. If $s < S$ then the parameter s is increased in one also the transition to step 3 is performed.

Step 5. The set $\overline{\Im}$ is formed according to the schedule built on steps 1-4 of the algorithm. If the set $\overline{\Im}$ is empty, then it is possible to assign that of any duration within the planning horizon and the process of finding an approximate solution is completed successfully. If the set $\overline{\Im}$ is nonempty, then the transition to step 6 is performed.

Step 6. Problem (8) is solved. Let t_1^* and t_2^* be the optimal values of variables t_1 and t_2 in this problem. If the value of the criterion in (8) is 0, then t_1^* and t_2^* set the time for maintenance, train schedule does not need to be rebuilt, the assignment process is completed successfully. If the value of the criterion in (8) is different from 0, then the set $\aleph' = Z' \cap \{k \in Z': \text{t}_\text{k}^{\text{end}} \leq \text{t}_1^*\} \cap \{k \in Z': \text{t}_\text{k}^{\text{start}} \geq \text{t}_2^*\}$ is formed and the transition to step 3 is performed.

Step 7. The parameter s is assumed to be equal to 1, the sets $\aleph_p, p = \overline{0, S}$ are empty.

Step 8. The minimization problem (9) is solved under constraints (1)–(3), (7), (10) and an additional condition: $\delta_{i,j,k} = 0, i \in \Im_s, j = \overline{1, J+1}, k \in \aleph'$.

If there is a solution to this problem, then a set of numbers of "sub-platforms" $\aleph_s$ occupied besides trains by numbers starting s is formed, and the transition to step 9 is performed. If there is no solution, then the search for an approximate solution is completed unsuccessfully.

Step 9. If $s = S$, then t_1^* and t_2^*set the time for that, the search for an approximate solution is completed success. If $s < S$, then the parameter s is incremented via one as well as the transition to step 8 is performed.

Step 1 of the algorithm requires a comment[10]. In , it was proposed to split the set of trains in the direction, i.e. the sets of $\Im_s$ were formed according to the principle of finding train numbers in them, which had the same departure vertices, as well as the same destination vertices. The fewer elements in the set, the smaller the number of this multitude. With this splitting, we will call the above algorithm an algorithm in the direction (algorithm 1). It is possible to propose another way of splitting, namely: by increasing the time of the readiness of trains for departure. So, the set $\Im_1$ will consist of the train number with the earliest time of readiness for departure, $\Im_2$ with the second, etc. Thus, for this approach to splitting a set of trains, it will turn out to be $S = I$, $a\Im_s$ consisting of the train number with the latest time
Ready to depart. If several trains have the same time of readiness for departure, then for a train with a large number, the index of the set in which this number is included should also be greater. With this splitting, we will talk about the algorithm by readiness (algorithm 2). In fact, algorithm 2 is supposed to search for the schedule sequentially by one train. A similar approach was used in [22, 23] when the train schedule at the station was supposed to be built for each train separately, and the schedule of shunting locomotives was built for each shunting operation separately[24].

7. Example

Reflect railway network epitomized by way of a multigraph G in Figure 1. Part of the edges is highlighted by a dotted line to display the multi-level connection of double railway roads. The numbering of the roads in the amount is gone astray: if double next to vertices connect double edges, i.e., double paths, at that time edge denoted via a direct line takes the number 1, and the other one has the number 2. The vertices of also leaving endpoint of trains are given by the same initial data used in [25], i.e., it is required to skip $I = 62$ trains, and there are $K = 1249$ "sub-platforms" for transportation. Detailed information about the direction of trains and the rules of movement along the "sub-platforms" can be found in Let's put $= 12$ and $c_1 = 1, c_2 = 1, c_3 = 1, t_1^0 = 0, t_2^0 = 1441, d_i = 181, t_{i,k}^{\text{st.min}} = 0$ and $t_{i,k}^{\text{st.max}} = 121, T_{\max} = 1441$. Suppose it is necessary to perform repair work on path number 2 between the vertices with indexes 1 and 2.
Let's analyze the applicability and quality of algorithms 1 and 2 by specifying in Table 1:

The value of the criterion in (6) on the traffic schedule in the absence of the need to assign that, i.e., the value of the criterion in problem (6) with constraints (1)–(3) and (7) with fixed $\delta_{i,j,k}$,which are set in steps 1-4; The time interval for which is obtained at step 6. The number of trains that fall into calculated at step 6. The value of the criterion in problem (6), taking into account the need to assign, i.e., with restrictions (1)–(3) and (7) for fixed values of $\delta_{i,j,k}$,which are set in steps 7-9 and Δ different.

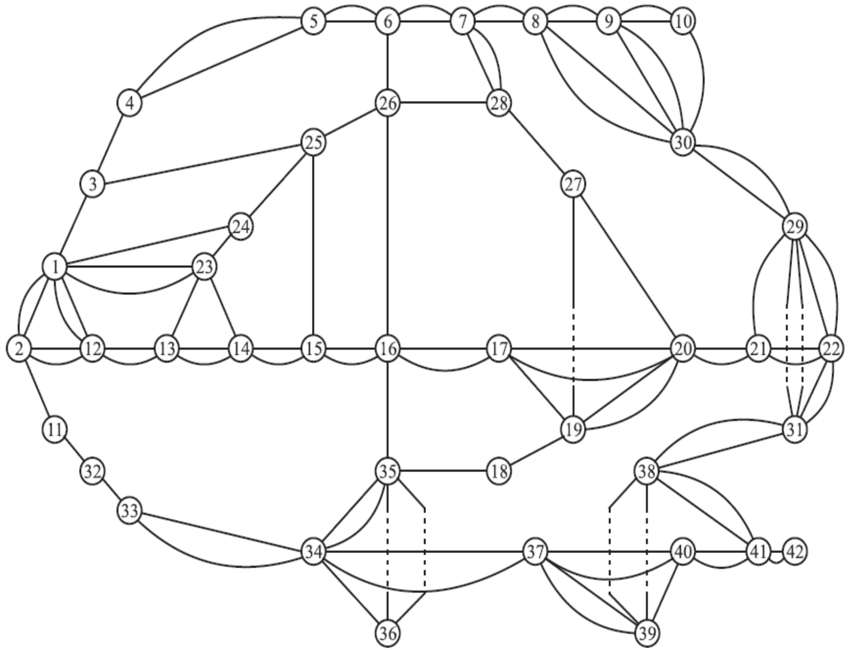

Figure 1: Multigraph of the railway network G

Table 1: Results of algorithms 1 and 2

Δ	Algorithm 1				Algorithm 2			
	The value of the criterion in (6) without taking into account	$[t_1^*, t_2^*]$	Value of criterion (8)	Value of criterion b (6) taking into account	The value of the criterion in (6) without taking into account	$[t_1^*, t_2^*]$	Value of criterion (8)	Value of criterion b (6) taking into account
601	26950	[0,601]	0	26950	27754	[0,601]	0	27754
691		[17,707]	2	27286		[17,707]	2	27840
721		[57,777]	2	27771		[57,777]	2	27910
781		[0,781]	3	28266		[0,781]	3	no solution
901		[0,901]	4	no solution		[0,901]	4	no solution

Table 2: Running time of algorithms 1 and 2 (in minutes)

Δ	Algorithm 1				Algorithm 2			
	Search for a schedule without taking into account	Search	Search for a schedule taking into account the total	Total	Search for a schedule without taking into account	Search	Search for a schedule taking into account the total	Total
601	20	0.08	0	19.08	8	0.08	0	8.08
691			15	33.08			8.2	16.18
721			24	42.08			9	16.08
781			15.79	34.86			–	–
901			–	–			–	–

As follows from Table 1, in terms of the criterion value, algorithm 1 gives better results than algorithm 2. Also, algorithm 1 allows you to find a solution in the case $\Delta = 780$, while algorithm two does not find a solution. Now let's analyze the time of searching for the timetable and then use algorithms 1 and 2 for different Δ. As follows from Table 2, algorithm one works significantly longer than algorithm 2, i.e., it is impossible to give clear preference algorithm one over algorithm two.

8. Conclusions

The paper considers the task of assigning maintenance on segments of the railway network. The optimization formulation is formulated in a procedure of a varied number lined programming problematic, which allows you to simultaneously find the train schedule on the railway network and the time interval in which repairs should be carried out. Due to the calculation hardness of explaining this complex,two algorithms aimed at discovering estimated results were planned. The presented informative example demonstrated the practical applicability of the proposed algorithms.

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