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Improvement of operational planning for shunting service on non-public railway lines

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Abstract. This article describes the problems, which arise when planning the shunting work on industrial railway transport, as well as suggests the ways of solving them. There are special feature specified here, which differentiate the shunting work at enterprises from the work, performed by the main transport. The necessity has been revealed and explained for the development of an automated software system, which will allow objectively evaluating the operational situation and choosing the most suitable option for performing the shunting work. There are basic optimization techniques described, which are used in the software product developed, as well as their importance and necessity has been substantiated. The main methods include: improvement with the help of registering the radii and curvature radii and curves of traffic areas; consideration of dependence of fuel consumption by shunting locomotives from the execution modes of shunting half-runs and the availability of time reserves; route selection depending on its length, the number of railroad switches, speed restrictions and travel time. Combination of existing methods of improving the shunting work with new proposals in one software package will allow receiving a convenient tool, assisting in operational planning, as well as in the identification of traffic bottlenecks and their management strategies. Computerization and automation of transport processes will have a positive impact on the development of connecting tracks and will help to improve the interrelation of the industrial and main line.

1. Introduction

Operational planning of execution of shunting work on connecting tracks is a complex multifactorial problem. Until recently, it has been addressed, from a scientific point of view, as an elusive goal but the cost for its solving have been incomparable with the expected profit from it. The rapid development of information systems and technologies over the last 10 years has reached a level, when it has become possible to solve this difficult problem in the light of the key and additional factors and at lower cost, compared with previous studies [1,2].

The state monopoly on trunk transport in Russia, Ukraine and CIS countries made it possible to raise funds for the development of technologies using information systems and computer technologies. At the same time, industrial transport could only use partially developed technologies. There was not enough money to develop their own information systems. This situation significantly hampered the development of industrial transport.

The main problems on industrial railway transport are:

- the need to take into account a large number of factors when planning the shunting work;
- the need to sort these factors into main and secondary (by their influence on the deviation in the process of work from the originally developed plan, taking into account the probabilities of the appearance of these factors).

General principles of shunting work include:

- security;
- adherence to regulations and instructions.

Differences are specific to the work, namely:

- the prevalence of shunting operations associated with the supply and cleaning of wagons;
- the disbandment of trains on unprofiled exhaust tracts;
- lack of a sufficient number of sorting ways;
- use of low-power locomotives;
- short distances of shunting half-races;
- low speed of movement;
- a significant number of sections of the road with curves of small radii and steep slopes;
- a small number of centralized tracts.

Errors in the planning of shunting work lead to financial costs. These costs are associated with additional rolling stock downtime, disruption of cargo loading plans. In general, this situation increases the pressure on the staff.

Informatization, automation and modeling of processes allow one to:

- identify bottlenecks in planning;
- reduce the load on the dispatcher;
- quickly find the best solutions for deviations from the plan.

The analysis of foreign [3,4] and domestic works [17,18] confirms the need for the development of an automated software package that will allow for the qualitative planning of manoeuvre work. The presence of an automated complex serves as an excellent statistical base for optimization, which was previously impossible, as it required high costs.

Creation of software systems, which model the transport processes, can drastically improve the scheduling, reduce costs and help the industrial railway transport to reach a new level of development.

2. Results

Nowadays, there are studies in the field of shunting work, which partially optimize it on various stages, which can be reflected in the following categories:

- normalization with the help of analysis of statistical data and adjustment of existing analytical calculation methods [3,4];
- optimizations, related to fuel economy during the shunting [5];
- optimization of shunting operation methods, such as reducing the number of shunting half-runs in case of sorting works at a different number of available railway tracks [6,7,8,9,10,11].

Sometimes, the cost saving in shunting work can be achieved as a result of evaluation of the company's activities and specific solutions, applicable on the basis of research. For example, laying of additional tracks, shunting locomotive reverse in order to improve the visibility and accelerate the work during the manoeuvres [12], replacement of existing motive-power units to more suitable ones in terms of capacity for specific conditions and so on.

2.1. Purpose and objectives of the study

The purpose of the work is to improve the operational planning of the shunting work on industrial transport with the help of model-based analysis. Also in this paper, we propose to combine the available experience in a general software product, as well as to make further optimizations in it.

In the process of the analysis of key factors, which influence the effectiveness of shunting work, the following problems have been identified:

- the finding of the optimal route of the shunting train. It is true for enterprises with an extensive network of railways;
- motion simulation of the shunting train with regard to radii, gradients of the route, speed restrictions on specific areas;
- selection of the optimal timetable for the shunting train;
- reduction of time and financial costs for the execution of shunting work.

2.2. Description of the principles of the developed complex for the improvement of shunting work

In the course of the executed studies [13,14], it was decided to use as a basis technological maps of shunting work, which represent tables, where all the executed manufacturing operations performed are described in detail.

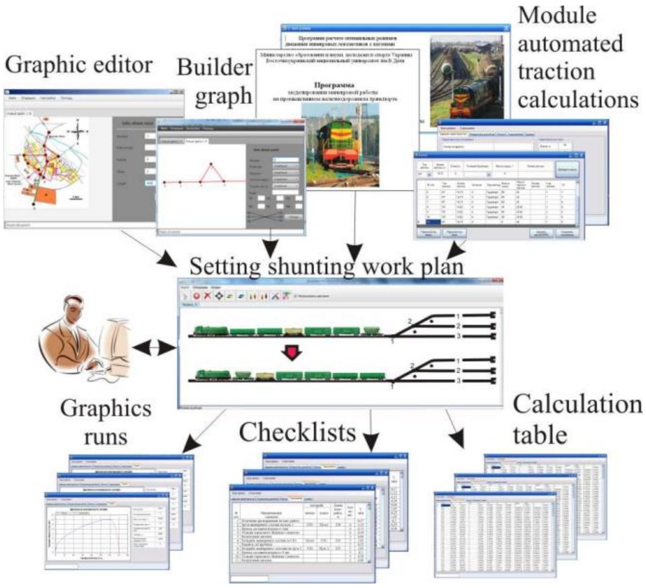

Figure 1. The operation scheme for the software package.

The principle of finding the time of shunting work.

1. In the first step the expert (engineer, TDC, station duty officer) generates a plan for performing shunting work indicating priority: minimizing the cost in time and fuel.

To form a plan, the expert chooses a shunting train with which the work will be carried out, indicates the beginning and the end of the route of movement on a topological map of connecting tracks, the number of cars, which needs to be attached or detached, then the next half-run and operation, etc. before the end of the work. The shunting management commands are selected from the list, and they are similar to those that are given under real maneuvers.

2. The second step is to create a graph of traffic routes of movement of the shunting train [15]. This function is performed on the basis of a specially developed algorithms for sections between track switches.

3. After the formation of the final graph of traffic routes of the shunting train, the information about the lengths of the half-run comes to the block of formation of non-stop routes, where there is a connection of half-run lengths made in non-stop traffic routes. The final lengths of half-runs and the information about the areas of movement come to the block of grade computations in order to calculate the travel time on these routes. The calculated time is passed for the formation of the temporary graph of movement of the shunting train.

4. After performing the above functions, there is the formation of a temporary graph and selection on the basis of the developed algorithms of the minimal time of the half-run.

5. After the formation of the plan for performing shunting work, the information about sequence of half-runs and the manipulations performed with cars (uncoupling/coupling) comes to the block of additional transactions determination between half-runs, where, based on normative documents, the information is displayed about additional transactions between them and is transmitted to the block of forming the process map. The information is displayed in a form of a table.

6. A special place in the diagram takes the function of optimization using neural networks. In the first step, there is a collection of data made for training in order to replace the function of grade computations later.

2.3. The mathematical representation of a program complex

A key role in the process of shunting work has a reserve of time. Based on the conducted research, it was decided to carry out the optimization based on the original terms. If there is a time reserve (R_t> 0), then the system is looking for options with minimum fuel consumption, otherwise (R_t = 0) – the minimum time:

$$f\left(T_{MP}\right)=\begin{cases}T_{MP}^{T}, R_t=0\\ T_{MP}^{G}, R_t>0\end{cases}\rightarrow \min \quad (1)$$

In general, the time of shunting work is calculated according to the formula as follows:

$$T_{MP}=\sum_{i=1}^{n}\left(t_{PRi}+t_{AOi}\right) \quad (2)$$

where t_{PRi} – the time of *i*-shunting half-run, min.; t_{AOi} – the time, spent on additional operations of *i*-shunting half-run, min., it is determined according to the applicable standards; *i* – the number of half-runs, $i=1..n, n>0$.

The time for additional operations is taken according to the developed standards and technological process [16].

The time of shunting half-run is the variable quantity, the calculations of which is proposed to perform taken into account specific conditions of work and the following factors:

$$t_{PRi}=f\left(S_M; l_{train}; l_i^{track}; R_p; \gamma_{gr}; \varphi; r_{LPC}; t_{sw}^{LPC}\right) \quad (3)$$

$$\begin{cases}l_{train}<l_i^{track}, i=1...n, n>0;\\ t_{sw}^{\min}<t_{sw}^{LPC}, t_{sw}^{\min}=3s.\end{cases}$$

where S_M – composition of the shunting train; l_{train} – the train length, m; l_i^{track} – the *i*-route length, m; R_p – reduced radius; γ_{gr} – slope; φ – thermal regime (heat, cold, wind, dampness); r_{LPC} – motion mode; t_{SW}^{LPC} – switching time from one controller to the next one, $t_{SW}^{\min}$ – minimal switching time from one controller to the next one, 3 seconds.

As R_t = 0, the formula (3) looks as follows:

$$t_{PRi}=f\begin{pmatrix}S_M; l_{train}; l_i^{track}; R_p;\\ \gamma_{gr}; \varphi; r_{LPC}^{\max}; t_{sw}^{LPC}\end{pmatrix}\rightarrow \min \quad (4)$$

where $r_{LPC}^{\max}$ – motion mode of the train on the maximum position of the controller (with a maximum allowable speed).

As R_t>0, the formula (3) looks as follows:

$$t_{PRi} = f\begin{pmatrix} S_M; l_{train}; l_i^{track}; R_p; \\ \gamma_{gr}; \varphi; r_{LPC}^G; t_{sw}^{LPC} \end{pmatrix} \to \min \quad (5)$$

where r_{LPC}^G – motion mode of the train at 4-5 position of the controller (with a minimum fuel consumption).

Next, let us describe the elements, which make up the following formula (3).

In the computing system, the shunting composition is represented in the form of a data structure:

$$S_м = \{D_{car}, C_м\}, \quad (6)$$

where D_{car} – list of cars related to the shunting locomotive, where each car has its own set of characteristics. $D_{car} = \{d_x^{car}\}$, where *x* – car's index. *Cм* – shunting locomotive.

The characteristics of the car are described as follows:

$$d_x^{car} = \{\delta; n_0; l_в; m_{empty}; m_{loaded}; m_{av}\}, \quad (7)$$

where δ – type of a car; по – number of axes of the car; l_c– car length, м; тempty – empty car weight, *t*; тloaded – loaded car weight, *t*; тav – average freight carload, *t*.

The shunting motive-power unit is described with the help of the following set of parameters:

$$C_м = \{a; P; v_T; v_i^p; m_l; l_m; F_k\}, \quad (8)$$

$$\begin{cases} v_i^p \le v_{all}^k \le v_T, i = 1...n, n > 0 \\ F_m < F_k \end{cases}$$

where *a* – axle configuration; *P*–diesel power; v_T – design speed; v_i^p – estimated speed on the *i* portion of line; T_l – weight on working order of the diesel-electric motive power unit; l_T – length of the diesel-electric motive power unit (distance between the axis of the automatic coupling); F_k – traction effort of the continuous rating; F_T – traction effort when breakaway; v_{all}^k – allowable speed on *i* portion of line.

One of the most complex parameters obtained is the path length of the *i*-th segment. The length of the section of movement is based on the length of the composition and its location on the topographic scheme of the station, taking into account the position of the remaining elements of the scheme (switches, employment paths). All this information is taken into account in the construction of the graph, from which the first non-stop motion segment is taken-the length of the shunting half-track.

The topological scheme of an industrial station can be represented as a combination of ordered sets of elements of the path development of different groups:

$$A_{oso} = A_{sa} \cup A_{rt} \cup A_{cf} \cup A_{tl}, \quad (9)$$

where A_{oso} –the ordered set of objects of the topological scheme of the station; A_{sa} is an ordered set of arrows; A_{rt} – an ordered set of paths; A_{sf} – an ordered set of cargo fronts; A_{tl} is an ordered set of traffic lights.

In this case, each set can be divided into subsets of objects (switches, paths, etc.)

Thus, any station can be represented as a connected graph $G = (V, E)$ with many vertices $V = \{v_1, v_2, ..., v_i\}$ and a plurality of ribs $E = \{e_1, e_2, ..., e_k\}$.

Each vertex will be characterized by the following set of parameters, which are further entered into the database: the vertex number, its mathematical coordinates, the paths that are adjacent to the given vertex, the direction and its direction, at what angle the path is adjacent to the arrow, the numbers of neighbouring vertices and how they adjoin in the top:

$$v_j = \begin{Bmatrix} N_j, X_j, Y_j, L1_j, L2_j, L3_j, A_j, B_j, c_j, C_j, \\ \varphi_j, N1_j, N2_j, N3_j, N4_j, N5_j, N6_j \end{Bmatrix}, \tag{10}$$

where N_j – the ordinal number of the vertex, which is described; X_j and Y_j –the coordinates of the vertex of the graph with respect to the origin; $L1_j$ – the path on which the given vertex is located; $L2_j$ and $L3_j$ – paths that are adjacent to a given vertex; A_j and B_j – side and direction of the vertex; c_j – the normal position of the switch; C_j – the actual position of the switch; φ_j – the angle of the switch; $N1_j$ … $N6_j$ – the points of contiguity of neighbouring vertices.

Each edge will be characterized by the following parameters:

$$e_j = \left\{H_j, O_j, W_j, Z_j, L_j, R_j, \gamma_{gr_j}\right\}, \tag{11}$$

where H_j – the ordinal number of the edge of the graph; O_j,W_j – the initial and final points of the edge; Z_j – the path to which this edge belongs; L_j – the length of the edge; R_j– the radius of the edge; γ_{gr_j} – the slope of the rib.

Also, when constructing a graph, account is taken of the characteristic of quantity sheet of tracks u_j^H, which is described in the formula 11.

$$u_j^H = \left\{G_j, A_j^H, Q_j, B_j^H, v_j, L_j^H\right\} \tag{12}$$

where G_j – track number; A_j^H – starting point of the track; Q_j – railroad switch, through which the following track goes; B_j^H – end point of the track; L_j^H – the total length of the track.

After selecting the starting and ending points of the movement, an algorithm is started which will build a directed graph of non-stop sections from the given graph of the station.

Thus, the length of the section of the shunting half-run.

$$l_i^{track} = f\left(v_j, e_j, u_j^H\right) \tag{13}$$

To consider the position of the switch point relative to the path, a codification is used that takes into account the contiguity and branch of the arrow.

To find the shortest path, the entire route is translated into a weighted undirected graph.

At the stage of preliminary analysis of the graph, the initial structure is transformed. On sections where the angle between the tracks is sharp, the composition must be passed to an additional point for the entire length of the composition and then go in the opposite direction to the desired path. To account for this, the angle between the paths along which the motion is carried out is calculated. If this angle does not lie in the range from 130° to 230°, then an auxiliary route should be used. From the intersection of paths forming an acute angle, all possible routes are analyzed. If they lie within the permissible limits of the angle of rotation, then they can be used as auxiliary ones. If an auxiliary path is not found, then the route is considered false, it is impossible to pass through, and the program will search for a new one. The graph is transformed by adding a new time vertex that simulates a change in the direction of the composition.

To find the shortest path, the algorithm "A is old" is used. All the paths that lead from the initial vertex to the final one are looked through step by step, until there is a minimum. With the help of the heuristic function, the algorithm "A old" assumes where to go and cuts off paths that will not lead to the end point. When you select a vertex, the entire traversed path is taken into account.

At the beginning of the work, nodes adjacent to the initial nodes are looked at; let us select the one of them that has the minimum value of $f(x)$, after which this node is expanded. At each stage, the algorithm operates with a set of paths from the starting point to all the vertices that are not yet open, which are placed in the priority queue. The priority of the path is determined by the value of $f(x)$:

$$f(x) = g(x) + h(x), \tag{14}$$

where $g(x)$ – the cost of reaching the considered vertex (x) from the initial point; $h(x)$ – the heuristic estimate of the distance from the considered vertex to the finite one.

The algorithm continues its work until the $f(x)$ value of the target vertex is the smallest. Of all solutions, a solution with a minimum value is chosen.

3. Discussion

The principles of better planning of shunting work, discussed in the article, have separately shown to be effective, which suggests that their synthesis into each other will give the intended positive effect. This method is planned for introduction in order to confirm and substantiate the conclusions of the study. Nevertheless, even at this stage the parts of the complex look like a finished software product and are used in the training of students in the course of theoretical training in the relevant disciplines.

The relevance of the results obtained in the article, is confirmed by similar developments in the field of transport both in domestic [17, 18] and foreign articles and complexes [6-8,10,11], which have been successfully introduced and continue to be implemented.

The following method is aimed at reducing the impact on employees, as well as at reducing the impact of the human factor on the process. It will also allow controlling the process better and revealing the reasons for the deviations from the selected option

4. Conclusions

This article presents a method of improving the planning of shunting work on non-public railway tracks. Its basic idea is to combine the existing solutions of many problems in one software package, allowing automating the planning work by its modeling. To carry out this task, there were main key points identified, the implementation of which allowed one to move closer to the goal.

Firstly, the software module has been developed - station scheme builder, which converts the layout of tracks into the graph with the further search of non-stop traffic routes and selection of the minimal route according to the travel time.

Secondly, for receiving the time for shunting work, there have been the automated way of forming the routing chosen where the half-run time is calculated with the help of the method of grade computations, when the time for additional operations between the half-runs and the type of shunting work performed is taken into account.

Thirdly, the grade computations were automated in the form of a special module, which was also linked to the check of possibility of traffic on the routes determined by the graph of connecting tracks.

Fourthly, the fact was also taken into account, that significant influence on the shunting half-run has the choice of the mode of work. This is reflected in the formulation of the search task for the time of shunting work. In the case of presence of the reserve time, the grade computations are performed, aiming to minimize the fuel consumption during the shunting half-runs. If there is no reserves, there is a search made for the minimum time spent on the half-run and on shunting work at the highest position of the controller.

Fifthly, the presented software package allows to determine in advance the time of shunting work, as well as to adjust it in the process of performance in the event of any impediments, which prevent the execution of the plan exactly with the calculated variant.

The above-mentioned principle should greatly help the planning process of shunting work and identify any "bottlenecks" in this process.

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