Hierarchical Polymodel Complex of Combined Planning of Transport and Logistics Systems

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Abstract— **the paper covers the problem of combined planning of functioning (movement and loading/unloading) of a group of trains combined in a single logistics network. The analysis of the main aspects is carried out, the proposed approach to solving the problem by application of an original multi-model complex describing the processes of group planning on the example of trains is described. The proposed method is based on the use of combined methods (Floyd's method, Boltyansky's method of local sections, branch and boundary method) to solve this non-stationary large-scale problem.**

Keywords— integrated planning; complex technical object; coordination of model; transport and logistics network; simulation systems; integrated planning methods

I. PROBLEM STATEMENT

Let us consider the classical problem of the job scheduling theory, namely the group planning of trains delivering universal cargo at the stations within a single railway network. The problem has natural limitations considering the impossibility of locating more than one train at same railway section at any time. And each station may be occupied by a single train for loading and unloading at each moment. Fig. 1 shows an example of a logistics network containing 3 trains, each can potentially deliver the goods to one of the three stations.

Let the main solution quality indicator be the total penalty for violation the delivery due times. The main goal is to minimize this indicator. Further, the article will introduce additional indicators of planning quality, taking into account the energy efficiency of the routes to the selected station for each of the trains (HCS).

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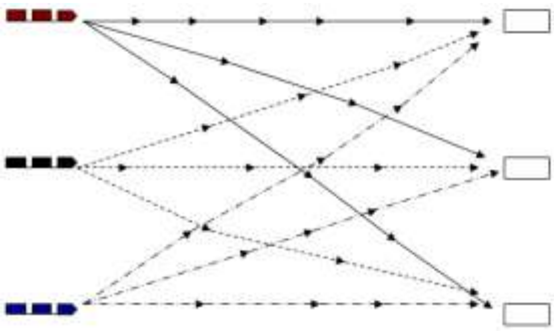


Fig. 1. Logistics network example

II. SIMULATION MODELING EXPERIMENTAL BOOTH

The RFID radio-frequency identification system is supposed to be used for locating stations and trains making up the logistics network. This distributed system provides remote access to information about the movement of trains and the condition of the relevant cargo, using the passive, semi-active or active marcs [6]. Each of these marcs includes a unique identification code that is read by RFID readers. The reader emits radio signals with a certain periodicity, which are re-emitted by the marks that appear in its electromagnetic field. The transmission of identification codes of the markers in the field allows to determine the train position with an accuracy of several meters, depending on the types of labels and readers.

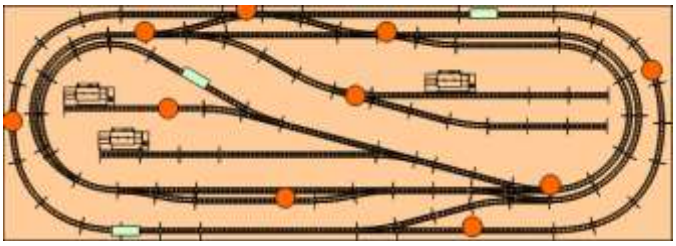
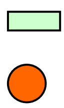


Fig. 2. Model of logistics network



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Starting in 2014 the scientific staff of SPIIRAS create a simulation and modeling experimental booth (see Fig.2), which is aimed to verify the solution of the regarded planning problem. The simulated railway network is divided into sections, containing RFID readers at each end, allowing to determine the position of each group planning object and its velocity at each time. The development of this booth is caused by the essence of firstly, calibration of train models of and, secondly, checking the feasibility of the plans for the dynamically changing external conditions.

III. Hierarchic multi-model complex

The regarded problem of multiple trains movement planning is solved by creating an original hierarchical polymodel complex (HPC). At its lower level the movement of a single train to a given station, taking into account the spatial and technical constraints, is planned and modeled. A dynamic motion model and algorithm are used to observe the restrictions and ensure a minimum of the specified travel time and a minimum of electric power consumption for traction for specific areas that are potentially included in the route of each train. For this, the following model is used, where s is the train coordinate (the point of the spatial position of the train):

$$\frac{dv}{ds} = \frac{1}{v}[u_f f(v) - u_r r(v) - u_b b(v) - w(v) - g(s)] \quad (1)$$

$$\frac{du}{ds} = \frac{1}{t_{sw} v} \quad (2)$$

$$\frac{dt}{ds} = \frac{1}{v} \quad (3)$$

where u_f, u_r, u_b – coefficients of traction, recuperative and mechanical braking, depending on the current position of the thrust controller, $w(v)$ – natural movement resistance, $g(s)$ – railway track slope at a given coordinate.

Quantitative and dimensional characteristics of the train taking into account the transported cargo, the force coefficients for the control components, as well as the resistance coefficients are to be calibrated to ensure the reliability of the model and the compliance of the built model plan of a particular train. The given dynamic model is part of the model-algorithmic support, solving the problem of planning the movement of one train to the station, selected in the solution of the corresponding planning tasks at the upper levels of the HPC. The computation of this stage results in the optimal trajectory, ensuring energy efficiency and allowing to calculate the time of the route with regard to the characteristics of the train and railway network section.

The next stage of integrated planning is a static model of the train group movement. The passage of each section of the path, limited by a pair of RFID readers, is considered as a technical operation χ carried by train A_i. The initial spatial position of train A_i, regarded to move towards station B_j, will correspond to the operation $x_{i\chi}^{(j)}$ (the symbol of the operation of the train A_i to the station B_j via the railway path consisting of sections χ). Using the standard Floyd algorithm the shortest distance from the initial spatial location of each train A_i to each station B_j is computed separately [3]. The calculated (generated) movement plans of each train are input data for coordination planning, carried out at the third level of the HPC.

In the context of group planning the mathematical model of the complex of operations $D^{(i)}$ is considered, corresponding to the passage of each of the sections of the path of a single train. To achieve this, we introduce a non-negative value $x_i = \sum_{\chi=1}^{S_j} x_{i\chi}{}^{(j)}, \forall j$, which we will call the state of this logistics operation. Its change in time is described

$$\dot{x}_i = \sum_{j=1}^{3} \sum_{\chi=1}^{S_j} \omega_{i\chi}^{(j)}(t) u_{i\chi}^{(j)} , \quad (4)$$

where $\omega_{i\chi}^{(j)}(t)$ — the normalized intensity of the operations obtained in the earlier stages of the complex modeling, $u_{i\chi}^{(j)} \in \{0,1\}$ – control 1 or 0, depending on whether the train follows the specified section or not. Along with (4) we introduce differential equations

$$\dot{y}_i^{(j)} = \sum_{\chi=1}^{S_j} u_{i\chi}^{(j)} , \quad (5)$$

with which we estimate the total movement time of train A_i to station B_j.

In accordance with the substantive statement of the problem in each moment of time each train can move to a single selected station and any station may be occupied by a single train. Then the control actions must satisfy the following restrictions:

$$\sum_{j=1}^{n} u_{i\chi}^{(j)}(t) \le 1 \ \forall i, \forall \chi; \ \sum_{i=1}^{3} \sum_{j=1}^{3} u_{i\chi}^{(j)} \le 1 \ \forall \chi;$$
$$\sum_{i=1}^{n} u_{i\chi}^{(j)}(t) \le 1 \ \forall j, \forall \chi; \ u_{i\chi}^{(j)} \in \{0, 1\} \ \forall i \ \forall \chi \ \forall j; \quad (6)$$

The restrictive equations

$$u_{i\chi}^{(j)} \left(a_{i(\chi-1)}^{(j)} - x_{i(\chi-1)}^{(j)} \right) = 0, \forall t , \quad (7)$$

determine the sequence of the sections to the stations included in the possible routes of the train A_i. Analyzing the constraints (7) shows, that $u_{i\chi}^{(j)}(t) = 1$ can only be in the case where all immediately preceding operations $D_\chi^{(i)}$, are complete, i.e. $\left(a_{i(\chi-1)}^{(j)} - z_{i(\chi-1)}^{(j)}\right) = 0, \forall t$.

Let the following functions serve as quality indicators for logistics problem solution:

$$J_1 = \int_{t_0}^{t_f} d\tau = t_f - t_0 \tag{8}$$

$$J_2 = \sum_{i=1}^{3}\sum_{j=1}^{3}[(a_i^{(j)} - \sum_{\chi=1}^{s_j} z_{i\chi}^{(j)})^2 (z_{i\chi}^{(j)})^2 + \sum_{\chi=1}^{3}\left[z_{i\chi}^{(j)} g_{i\chi}^{(j)} + \frac{\left(a_{i\chi}^{(j)}\right)^2}{2} - h_{i\chi}^{(j)} \right]^2 (z_{i\chi}^{(j)})^2] \tag{9}$$

$$J_3 = \sum_{i=1}^{3}\sum_{j=1}^{3}\int_{t_0}^{t_f} \eta_{iS_j}^{(j)}(\tau) u_{iS_j}^{(j)}(\tau) d\tau \tag{10}$$

where J_1 quantifies the total time spent on the implementation of a coordinated train plan, J_2 – allows to compute the losses from incomplete implementation of the complex of works on cargo delivery, J_3 determines the total penalty for violation of delivery due times, where $\eta_{ij}(\tau)$ – monotonously increasing time functions, determined on known startup or finish due times of logistics operations.

Thus, the problem of optimal planning of movement and unloading of the trains is reduced to the search for a valid program control of the dynamic system (4)–(5), which ensures the fulfillment of the relevant boundary conditions, as well as satisfying the specified restrictions (6)–(7) and delivering extrema to the quality indicators (8)–(10). The solution of this problem of joint planning allows to identify the dynamic priority of the section passage operations between the two readers for a particular train. The dynamic priority also takes into account both the need to pass all the preceding sections and the continuity of a particular logistics operation. In addition, in this case, the uniform distribution of resources (railway tracks) within the network schedule of the movement of vehicles is ensured.

At the final stage of the HMC the computed plan of group motion is tested for robustness and stability and amended (if necessary) on the basis of the results of simulation of their implementation. The imitation provides the feedback used for iterative rescheduling, which in turn allows to increase the robustness of the calculated plan and introduce the corresponding functional redundancy (reserve) into the complex plan. This allows to compensate for the impact of possible (at the stage of implementation) random factors and thereby to reduce the probability of violation of the due time of cargo delivery at the destination [5].

IV. CONCLUSION

The proposed approach to solving the non-stationary problem of the theory of schedules has certain advantages over traditional solutions of this class of problems. The developed original HPC allows to decompose the solution of the initial planning problem into four main stages. Within the proposed dynamic decomposition of the initial problem the dimension of the planning problems solved at each time is significantly reduced. Combined planning allows to consider different types of restrictions imposed on the movement of trains and the influence of disturbances that violate the robustness and stability of the constructed plans. To date, the created simulation and modeling booth carries out preliminary experiments on the calibration of models of the movement of train.

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