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Improvement of the technology of accelerated passage of low-capacity car traffic on the basis of scheduling of grouped trains of operational purpose

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Abstract

One of the main directions of increasing the efficiency of the operating model of the railways functioning is the reduction of logistics costs in the transportation of wagon and group shipments due to the improvement of the technology for accelerating the passage of low-capacity railcar traffic on the basis of the organization of the circulation of grouped trains of operational purpose, taking into account the synchronization of the plan for the formation of grouped trains with a schedule of traffic. In order to provide the railway system with the properties of adaptive control of low-capacity railcar traffic at the networks of large dimensions, an optimization mathematical model has been developed. To optimize this mathematical model, it is proposed to use a real coded genetic algorithm. The coding and decoding process of the chromosome of the genetic algorithm has been formed, which reflects the technological features of the implementation of the train formation plan of the grouped trains of operational purpose. This approach will allow to increase the level of organization of transportations and to accelerate the delivery of cargoes and to increase the competitiveness of railways in the market of transport services.

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1. Introduction

One of the main ways to increase the efficiency of the operating model of the railways is reducing logistics costs during transportation of single wagonload [1] and group dispatches. Significant reductions in freight traffic on the railways of both the European Union [2] and Ukraine led to an increase in the duration of idle cars under accumulation at sorting stations, leading to non-compliance with cargo delivery times, an increase in car turnover, and as a result, a decrease in productivity [3]. At the same time, in the sector of carriage and group dispatches, competition with road freight transport is acute [4]. This situation requires the railways to solve the problem of improving the existing technologies of the transportation process related to the formation, organization and dispatch of freight trains based on a concept that will allow flexibility in the operation of railways, taking into account changes in the formation of carload to trains.

Under such conditions, research aimed at improving the technology of accelerating the passage of low-capacity car traffic flows based on the organization of the circulation of operative group trains, taking into account the synchronization of the group train formation plan (TFP) with the timetable, is relevant. The necessary basis for solving the problem is the use of modern mathematical methods for developing timetables for freight trains on the principle of the precise implementation of the established corridor.

The organization of group trains is based on the principle that at the agreed stations of group train routes there is a sequential change of groups of cars in the train, which makes it possible to reduce simple carload dispatches compared to their idle time when cars accumulate for a unit train. The plan for organizing such trains should be based on monitoring the number of cars located at the sorting stations, and making prompt decisions about sending these cars and the timetable of their movement. The effectiveness of network formation of chains of interconnected group trains depends on the correct construction of the train timetable, which must be synchronized at the stations of the exchange of groups of cars. The formalization of the problem of coordinating the timetables of the movement of mobile units was developed in the field of timetable synchronization problem [5]. The formulation of such tasks is very common in road transport. For example, in the work [6], the task of vehicle departure time optimization was formulated within the framework of the task of vehicle routing problem with time windows. ILP-formulation is proposed that minimizes the total duty time. An interesting approach is synchronization of the movement of buses in the city, taking into account the random travel time [7].

The statement of timetable synchronization problem is also known in the field of railway transport [8]. The study [9] has developed a mathematical model for mixed-integer-programming (MIP) optimization model that minimizes the interchange waiting-times of all passengers. The developed algorithm for solving this mathematical model was tested on the Mass Transit Railway system in Hong Kong. Numerous previous results indicate that our approach greatly improves synchronization compared to current practice of using fixed paths and departure times. Results demonstrate that the proposed model is effective in improving the transfer performance in that they reduce the connection time significantly. In work [10], the model of timetable coordination of first trains in urban railway networks is developed, based on the importance of lines and transfer stations.

Known research directly related to the improvement of timetables Single Wagonload (SWL). In study [11], an agent-based tool called GüterSim was developed based on existing MATSim software. GüterSim models the routing of freight cars, as agents, in accordance with the routes in Switzerland’s real SWL network and production schemes. However, this mathematical model is imitative, which uses the existing timetable on the railway, helps to investigate the efficiency of the organization of cars into trains, but does not allow to find a synchronized timetable of group trains on the network. In work [12] describes the decision support system for the train dispatcher, developed at the Norfolk Southern Railroad in the United States, which consists in a partial enumeration of the schemes of admission with the aim of drawing up an effective train timetable. The plan for the passage of trains drawn up by this method may include a period of up to a day. Such a plan can be accomplished by embedding reserves in it, but it is not optimal with respect to the synchronization of train movement.

Considering that most of the studies did not focus on improving the technology of accelerated passage of SWL dispatches based on the synchronization of the timetable of operative group trains, this study aims to develop a method for optimizing the timetable and to prove the effectiveness of the proposed approach compared to existing transportation technology.

2. Mathematical formulation of the problem of synchronization of the timetable of operative group trains

Taking into account the complexity of solving the problem of synchronization of the timetable of operative group trains, it is proposed to develop a mathematical model for calculating the timetable of group trains at the network level. The main feature of the timetable of group trains is the importance of determining the departure time from the initial station and, accordingly, the arrival time of the car group exchange station, where the timetable should take into account the time of maneuvers at the station by exchanging the car groups, ending the formation of the group train and sending this train to the next station exchange of groups of cars with the possibility of linking the arrival of this composition with the arrival of a group train from another direction.

According to the research [13,14], a mathematical model for synchronizing the timetable of group trains at the stations of the exchange of groups of cars can be represented as an objective function that minimizes the total idle time of groups of cars at the stations of exchange and restrictions of the type:

$$F(X_{ki}, H_i^s, I_{(k,k+1)i}) = \sum_s \sum_i \sum_j \sum_k Wt_{kij}^s \to \min \tag{1}$$

$$X_{k,i} \geq 0,\ X_{1,i} \leq I\max_i;\ 1 \leq k \leq \mathrm{f}_i, \tag{2}$$

$$X_{k=\mathrm{f}_i,i} \leq T,\ 1 \leq i, j \leq N, \tag{3}$$

$$I\min_i^s \leq X_{(k+1)i} - X_{ki} \leq I\max_i^s, 1 \leq s \leq S, \tag{4}$$

$$H\min_i^s \leq H_i^s \leq H\max_i^s, \tag{5}$$

$$at_{k,j}^s > dt_{k,i}^s,\ 1 \leq i, j \leq N \tag{6}$$

where:

- k- the number of the freight train
- i,j - travel routes $i \neq j\ i = \overline{1,N}$, $j = \overline{1,N}$, $i, j \in N$
- N- the number of possible routes for group trains
- $X_{k,i}$ - variable, corresponds to the time of departure of the $X_{k,i}$ - train on the i route, min
- H_i^s - variable, models the time spent by the train at the group exchange station, min
- $I_{(k,k+1)i}$ - variable, models various variants of departure intervals along the route of group trains, $I_{(k,k+1)i} = X_{(k+1)i} - X_{ki}$ min
- Wt_{kij}^s – duration of the exchange of groups of cars at the s station between group trains can be determined by the expression $Wt_{kij}^s = at_{kj}^s - dt_{ki}^s$, min
- $at_{ki}^s = X_{ki}^s + t_{ki}^s + H_i^s$ – time of departure of trains from the group exchange station, min
- $dt_{ki}^s = X_{ki}^s + t_{ki}^s$ – time of arrival of trains at the group exchange station is calculated by adding the train

departure time to the time t_{ki}^{s} required for the train to go to the s station, min

- f_i – the number of departures (frequency) of group trains that are timetabled on the route i in the interval $[0,T]$, $k=\overline{1,F}$, $f_i \in F$, trains
- T- the planning period, which in accordance with the formulation of the task, should be taken equal to days, T=1440 minutes
- $I\min_i^s$ - minimum interval between trains, min
- $I\max_i^s$ - maximum value of the interval between trains, min.; s-the number of the station for the exchange of car groups $s=\overline{1,S}$
- $H\min_{ij}^s$ - minimum interval between the arrival and departure of two trains at the station of exchange of groups of cars s required for carrying out operations on the exchange of groups of cars, min
- $H\max_{ij}^s$ - maximum interval between arrival and departure of a group train at the station of exchange of groups of cars s, min

The constraint (2) determines the need to send the first group train on each route i within the interval $[0, I\max_i]$. Constraint (3) establishes the condition under which the departure of the last group train must be within the planned period T. Constraints (4-5) determine the need to respect the inter-train interval and parking time of the group train at the group exchange station. Constrain (6) excludes unacceptable variants of group train passage schemes at the car group exchange station, that is, early reception and dispatch of group trains at the car group exchange stations are excluded. It should be noted that the solution of the proposed mathematical model is possible only under the condition of the admissibility of the problem, that is, with the existence of carrying capacity in the railway sections in the conditions of passenger traffic.

3. Solution of a mathematical model using Real-coded Genetic Algorithm

The proposed model with the objective function (1) and constraints (2-6) belongs to the class of linear programming problems of high dimensionality. To improve the accuracy and speed of solving this mathematical model, it is proposed to use an optimization method based on real-coded genetic algorithm, RGA) [15].

To implement the mathematical model within the RGA, it is proposed to generate the following RGA chromosome code. The chromosome is proposed to be represented as a set of variable parameters of the model, taking into account the restrictions on their ranges and their construction into one numerical vector consisting of two parts

$$CH^z = (C^1, C^2),\ z=\overline{1,Z}, \tag{7}$$

where z - the number of the chromosome in the population Z. The first part $C^1 = (\underbrace{c_1^l, c_2^l, .., c_k^l}_{i=1}, \underbrace{c_1^l, c_2^l, .., c_k^l}_{i=2}, ..., \underbrace{c_1^l, c_2^l, .., c_k^l}_{i=N})$ models the variable $c_k^l = X_{k,i}$ - the departure time of each k train on the route i, where, $k=\overline{1,f}$, $c_k^l \in [0, I\max_i]$, $I\max_i \in [0, T=1440]$ min, $l=\overline{1,M}$ where M- the total number of genes in the chromosome CH^z. The second part $C^1 = (\underbrace{c_1^l, c_2^l, .., c_k^l}_{i=1}, \underbrace{c_1^l, c_2^l, .., c_k^l}_{i=2}, ..., \underbrace{c_1^l, c_2^l, .., c_k^l}_{i=N})$ models the variable $b_{k,i}^l = I_{(k,k+1),i}$- the departure interval between two threads of group trains on the route section, where $b_{k,i}^l \in [I\min_i, I\max_i]$, min.

To evaluate the solution to this mathematical model within the fitness function of the genetic algorithm, a procedure for decoding the chromosome is developed. At the first stage, in accordance with the values of the variables, a chain of operations is built up in time with each thread of the group routes. After that, the agreed version of the group train timetable is estimated by the target function, which is a penalty function, including optimization criterion (1) and penalty function for observing the limitations of the model (2-6). Thus, it is proposed to turn the conditional optimization problem into RGA into unconditional [16,17], of the form

$$\mathrm{Fit}(CH^{Z}) = \sum_{s}\sum_{i}\sum_{j}\sum_{k} Wt^{s}_{k,ij} + \lambda\left(\sum_{\kappa=1}^{Z}(h_{\kappa}(x))^{2}\right) \rightarrow \min, \tag{8}$$

where: λ - the penalty function parameter, $\lambda > 0$ and $h_{\kappa}(x)$ - restriction of the inequality of the problem (2-6), reduced to a form $h_{\kappa}(x) \leq 0, \kappa \in \mathrm{K}$.

For practical application, a software implementation of the solution of a mathematical model based on RGA is performed.

4. Experiments to assessment of the effectiveness

To test the effectiveness of solving the optimization problem of synchronizing the timetable of group trains based on the RGA, it is proposed to conduct an experiment on the following output of the train formation plan, shown in Fig. 1.

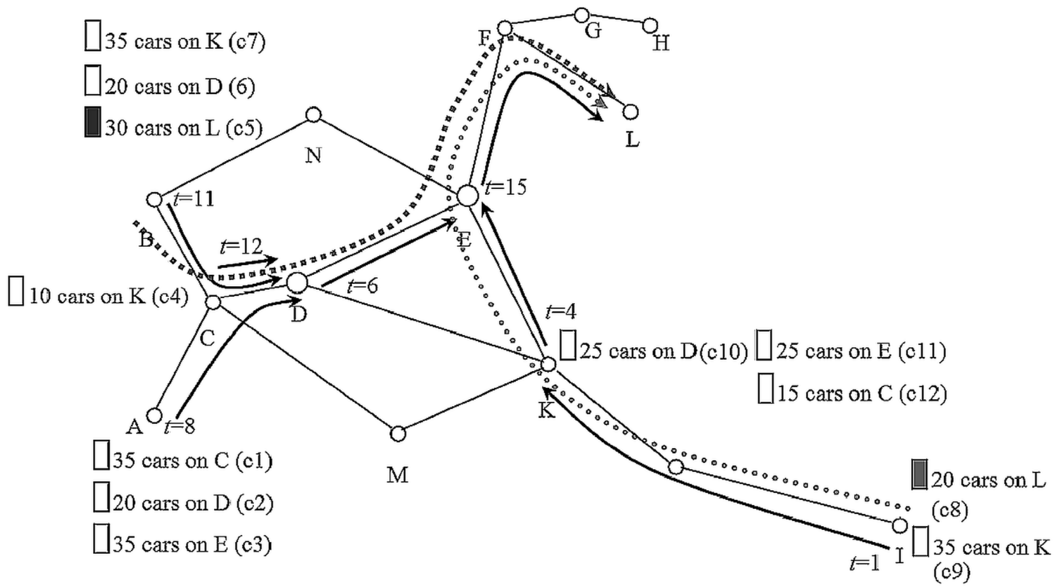

Fig. 1. Visualization of the route of groups of cars of low-power threads of distant assignments c5 and c8 on the graph of network *G*.

In accordance with Fig. 1 in graph *G* for group c5 from 30 cars following from station B to station L and group c8 consisting of 20 cars from station I to station L, there are the following routes: for group c8: from station I the two-group train with trains of the c8 and c9 groups is sent on thread *t*1; at station K, the core group c8 is combined with the group c11 and sent to the *t*4 thread to station E. Then the group c8 is combined with the group c5 to the thread *t*15, the group c5 together with the group c6 - to the thread *t*11. Group c5 unites with group c3 at station D and continues the route with thread t6 to station E. As noted above, at station E, group c5 unites with group c8 and a through train goes to the destination station L for thread *t*15. The dependence of the values of the fitness function of the developed RGA on the number of its iterations when searching for the optimal solution of the mathematical model is shown in Fig. 2.

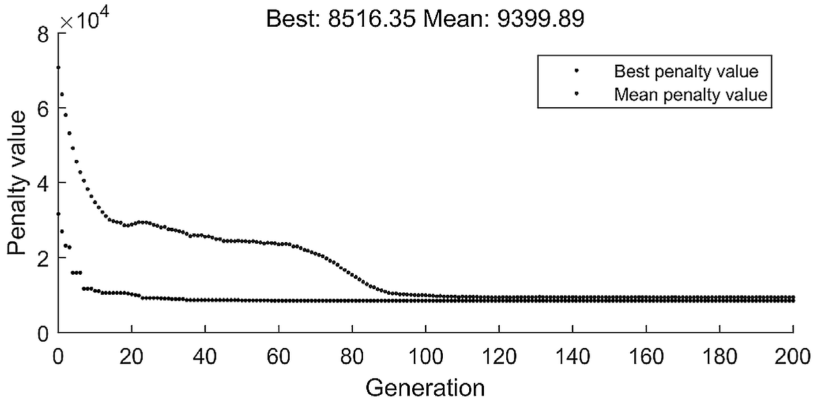

Fig. 2. Dependence of the values of the fitness function of the developed RGA on the number of its iterations when searching for the optimal solution of the mathematical model.

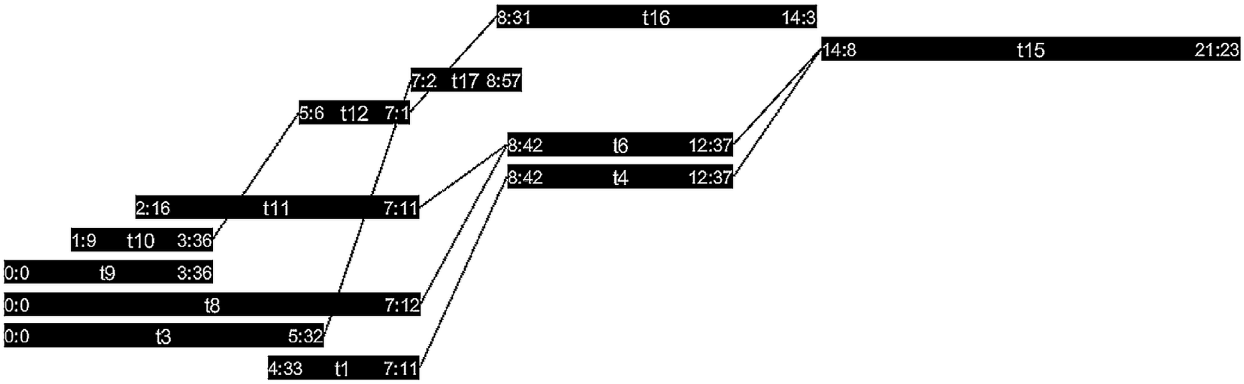

Fig. 3. The result of solving the optimization problem of synchronization of the timetable of operative group trains in the form of a Gantt chart.

Fig. 3 shows the calculation results in the form of a Gantt chart for a pre-set task of constructing a plan for the formation of operative group trains on a graph of the *G* network with 17 vertices. The abscissa of the graph displays the relative time from 0 to 1440 minutes. Dark rectangles (see Fig. 3) reflect the duration of movement of groups of cars in group trains to the appropriate thread. At the beginning and at the end of each rectangle is the specified time of departure and arrival. The name of the thread is reflected in the middle. The thin lines show the operation of re-linking the groups of cars between the respective threads of the trains.

According to the above data, the result of solving an optimization mathematical model is found for synchronizing the timetable of group trains, which was summarized to Table 1.

5. Comparative analysis of modeling results

To determine the effectiveness of the use of technology to promote low-power carloads of distant threads in operative group trains, it is proposed to evaluate the comparison of the costs of carriages and locomotive hours for the various options for their passage.

Table 1. The result of modeling on the dislocation of groups of cars and the number of timetable threads on the found route.

Group name	Number of group cars	departure station	destination station	Thread number on the route	Time in motion, *h*	Idle time at the station, *h*	Total time, *h*	Station name and time spent at the station (*h*)
'c1'	35	'A'	'C'	'*t*9'	3,61	0	3,61	[0]
'c2'	20	'A'	'D'	'*t*8'	5,53	0	5,53	[0]
'c3'	35	'A'	'E'	'*t*8,*t*6'	9,45	1,5	10,95	'D=[1.5]'
'c4'	10	'C'	'K'	'*t*13,*t*16'	7,46	1,5	8,96	'D=[1.5]'
'c5'	30	'B'	'L'	'*t*11,*t*6,*t*15'	15,09	3	18,09	'D=[1.5044];E=[1.5]'
'c6'	20	'B'	'D'	'*t*11'	4,38	0	4,38	[0]
'c7'	35	'B'	'K'	'*t*10,*t*13,*t*16'	9,92	3	12,92	'C=[1.5];D=[1.5]'
'c8'	20	'I'	'L'	'*t*1,*t*4,*t*15'	15,40	3.1	18,40	'K=[1.5];E=[1.51]'
'c9'	35	'I'	'K'	'*t*1'	4,70	0	4,70	[0]
'c10'	25	'K'	'D'	'*t*3'	5,54	0	5,54	[0]
'c11'	25	'K'	'E'	'*t*4'	3,92	0	3,92	[0]
'c12'	15	'K'	'C'	'*t*3,*t*17'	7,46	1,5	8,96	'D=[1.5]'

Based on a comparative analysis, it is proposed to evaluate the effectiveness of the three options for advancing car traffic flows: the current option provides for the passage of these groups of cars into single-group (unit) trains (see Fig. 4 a-part), other two options are based on the initial data of the group train formation plan (Fig. 4 b-part), one of which provides for securing group trains according to a certain timetable, and the other way around corresponds to the solution found for the proposed mathematical model for synchronizing the movement of operative group trains based on RGA, which given in this article.

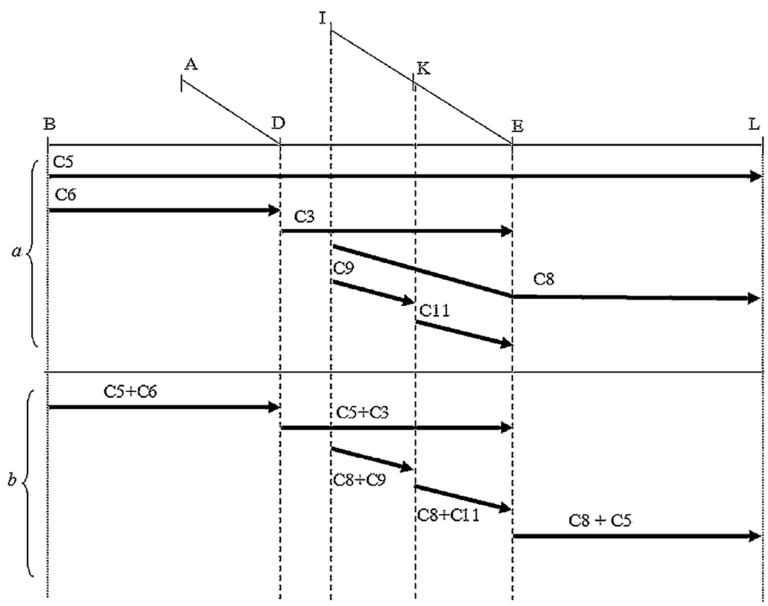

Fig. 4. (a) scheme of the plan for the formation of unit trains; (b) scheme of the plan for the formation of group trains.

The scheme of formation of single-group and group trains on the branched direction B-L is shown in Fig. 4. In the first option (Fig. 4 a-part), it is envisaged that each of the groups of cars follows the current plan of formation in single-group trains: groups c5 and c8 – in through trains from B to L and from I to L, respectively, and all other groups in district appointments.

From a comparative analysis of the above options it is possible to conclude that under the regulatory conditions for the TFP implementation, the option of sending to single-group trains is less expensive. However, the use of technology to promote low-power threads of long-range assignments (c5 and c8) provides for an increase in car idle time in accumulation over the regulatory period established by the current TFP.

The paper analyzes the feasibility of using various options for promoting low-power carriage flows c5 and c8, provided that their accumulation parameter increases from 9 to 15.5. From the analysis it is found that with the accumulation parameter exceeding $c = 12.01$, it is advisable to apply the TFP adjustment technology based on the organization of operative group trains according to an agreed timetable.

So, under equal conditions, with an increase in the accumulation parameter of single-group appointments of 10.7%, it is advisable to follow long-distance car traffic flows of single-group appointments in group trains to consolidate according to an agreed timetable.

For estimating the costs of given car-hours for each of the proposed variants of the train formation plan (see Fig. 4), it is proposed to apply an analytical method of calculating [18]. The results of the calculations of expenses for the four options are summarized in Table 2.

Table 2. Total expenses for various options for the promotion of low-power threads of distant appointments.

Name of the promotion option	Car hours costs	Reduced locomotive hours costs	Total reduced costs
Following in single-group trains (According to the TFP regulatory conditions)	3581	720	4301
Following in single-group trains (In case of violation of TFP standards)	3762	720	4482
Following in group trains without assignment according to an agreed timetable	3701	966	4667
Following in group trains on assignment according to an agreed timetable	3461	966	4427

Thus, on the basis of a comparative analysis of the reduced costs of locomotives and car-hours of idle time according to four options, the expediency of organizing operative group trains according to an agreed timetable is proved, which makes it possible to reduce the above costs compared to the option of following group trains without a timetable by 5.14%.

6. Conclusion

To formalize the synchronization technology of the timetable of movement of operative group trains at the exchange stations of car groups, an optimization mathematical model is developed, which, unlike the existing ones, allows to automate the system of linking the timetable for a large number of group trains at a network site of considerable dimension.

To solve this mathematical model, it is proposed to apply a genetic algorithm with a valid coding. The procedure is formed for encoding and decoding the chromosome of the genetic algorithm, reflecting the technological features of the implementation of the plan for the formation of operative group trains. The proposed procedure allows to reduce the running time of the genetic algorithm for large-scale problems and allows to accelerate the convergence of the algorithm when searching for a rational solution of the problem.

In the future, based on the obtained mathematical model and the method of its solution, it is possible to create a decision support system for calculating the timetable of group trains. Such approach will improve the organization of transportation, speed up the delivery of cargo and increase the competitiveness of railways in the transport market.

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