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TRAFFIC ORGANIZATION ON THE RAILWAY NETWORK AND PROBLEM OF CONSTRUCTION OF GRAPHIC TRAIN TIMETABLE

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Abstract

The organization of railway traffic is a complex decision-making problem. Its complexity results from the multiplicity of problems and from the number of factors, which should be considered. Amongst the research areas, concerning the organization of railway traffic construction of rational train timetable is taking the essential place. In the article was described technical-organizational conditioning of the construction of graphic train timetable. We presented mathematical models of the construction of train timetable, in which we took into account-selected boundary conditions. A way of solving a problem was presented also.

Issues of the construction of the graphic train timetable, technical-organizational conditioning of the construction of the graphic train timetable, the organization of the rail traffic and the formalization of the record of the construction of the graphic, boundary conditions and indicators of the quality assessment of the solution, the areas of research concerning the problem of the organization of railway traffic, correct preparing of the graphic timetable, mathematical model are presented in the paper. Introduced in outline mathematical model allows for pathing of trains on the graphic timetable in compliance with priorities of pathing.

Keywords: *railway transport, construction of train timetable, technical-organizational condition*

1. Introduction

The traffic of trains on the railway network, because of the need to keep the highest degree of safety and the appropriate degree of liquidity, must appropriately be structured. So that the traffic of trains will be possible there are involved many components of railway transport system. Among them, it is possible to mention elements of control command and signalling equipment, infrastructure, human resources, operators, means of transport and others. Connecting all elements with oneself should be carried out in this way so that they bring the beneficial effect due to appropriate using technical means and the smallest number of people needed for the service. An appropriate connection ensuring the fluid traffic of trains is an organization of the railway traffic.

As results from above, the problem of the railway traffic include many issues. The areas of research concerning the problem of the organization it is possible to divide basically in the ones, which concern the passenger traffic, and the ones, which concern the freight traffic. They stayed introduced in Tab. 1.

It appears from above dissertations that the organization of the railway traffic is a complex decision-making problem. The complexity results from the multiplicity of problems and from the number of factors, which should be considered. The majority of them have a relation with preparation of the work schedule of railways, according to which the movement on the railway network will take place [2]. One of crucial elements of the organization of the railway traffic is a construction of the rational train timetable (in Tab. 1 appropriate cells were marked on grey).

Preparing the rational train timetable is being conducted in two stages [8, 11, 12]:

– shaping of the transport offer, where the problem is: appointing rational courses of communication lines, allotting to the appropriate volume of the flow to the movement on individual

communication lines, the allocation of given type of the train set for the service of individual communication lines, allocation of the frequency of running to individual communication lines,
– construction of the graphic train timetable, where the problem is to outline the paths of trains on the canvas of graphic train timetable.

Tab. 1. The areas of research concerning the problem of the organization of railway traffic (ORT) [28]

AREAS OF RESEARCH OF ORT IN PASSENGER TRAFFIC	AREAS OF RESEARCH OF ORT IN FREIGHT TRAFFIC
1. satisfying of transport tasks	1. satisfying of transport tasks
2. guaranteeing the continuity and safeties of transports	2. regulating of norms of the trains' operation on railway stations
3. minimization of the journey time	3. regulating of lines' and railway stations' capacity
4. conducting the traffic of trains according to documentation	4. construction of rational train timetable and collating plans
5. ensuring comfort for passengers	5. preparing the competent labour organization of railway stations
6. providing the cost-effectiveness of the transport	6. conducting the traffic of trains according to documentation
7. adaptation of numbers and capacities of trains to the volume of flow	7. keeping records of indicators
8. correct rolling stock circulation	8. cooperation with entities in planned completion of transports
9. construction of rational train timetable	9. others
10. others	

The problem of shaping of the transport offer largely is regarding the problem of traffic flow distribution on the network [1, 14-16, 18, 20]. It should be aspire to make it in this way to guarantee the reliability and the effectiveness [13, 17, 19]. However, construction of the graphic train timetable is the process of preparing the correct organization of the railway traffic on the chosen fragment of the railway network. It consists in assigning specific hours of both departures and arrivals to specific operating control points and forwarding offices on the railway network in this way so that the movement will be conducted fluid and safe and so that it will met needs of all participants of the process of transport.

2. Issues of the construction of the graphic train timetable in literature

In polish literature was presented a wide description of the construction of the graphic train timetable on the example of the infrastructure manager PKP Polskie Linie Kolejowe S.A. Gołębiowski and Żebrak [9], Jacyna and Gołębiowski [8, 11] and Karoń with Skrzypek [21] described the process flow of the construction of the graphic train timetable in Poland. Gajda [7], Nowosielski [26] and Żurkowski with Pawlik [34] presented theoretical bases of the forming of the graphic train timetable. Woch [30] described a problem of the movement control after the riot of impediments in the railway network using of graphic train timetable. Wolfenburg [31, 32] described using of simulation models the directing of trains traffic on the railway line. In addition, it was presented the problems of mathematical modelling of the area of organization of the railway traffic on the railway network (Jacyna and Gołębiowski [11 12], Leszczyński [23]).

In international literature, a lot of place devoted to problems of the construction of the graphic train timetable. Hansen and Pachl [10] presented theoretical bases of the forming of the graphic

train timetable. Many publications are regarding the mathematical modelling of the construction of the graphic train timetable (Train Timetabling/Scheduling Problem – TTP/TSP) (among others Caprara et al. [3]). The research concerning the analysed problem were divided in two groups of issues – research on the cyclic timetable (among others Luthi [24], Serafini and Ukovich [29]) and noncyclic (among others Carey and Lockwood [4], Corman et al. [5], Oliveira and Smith [27]) train timetable. In international literature also was being described the problem of preparing timetable and optimal railway traffic operation management after occurrence of difficulties (Corman et al. [5], Meng et al. [25]).

The effect of the process of the construction is preparing the schedule of the ride of trains i.e. the train timetable, which is fulfilling the following functions [10, 22]:

– function of the planning – it allows for the adaptation of intensities of the transport service to volume of the passengers flow and freight, to changeable volume of transport tasks and permanent or immediate needs in the period usually of one year,
– function of the timetable – it allows for adapting of dates of running of trains and the number of stops to the volume of transport needs,
– crystallizing function – it allows for specify the conditions and possibilities of the transport, so as circulations of train sets, determining the roads of the transport and others,
– coordinating function – it allows to set communication conditions between individual trains and other means of transport on stations and between individual trains on the given railway line,
– organizational function – it allows for organising the functioning of railways and crews supporting the process of transport and influences the external environment of the railway transport.

Due to the fact that the graphic timetable is a demonstrative image of the railway traffic, it is performing many functions among which we can rank [6, 33]:

– checking the collision of trains on the open line,
– accurate arrangements of the place of overtaking oneself of trains on the double track line,
– establishing the functional dependency between the time and the place of being of running train,
– the evaluation of the capacity of the railway line and determining the degree of for its using,
– evaluation of the ability of the transport of railway line,
– determining conditions of rational using of locomotives and traction and conductor's crews.

Construction of the graphic train timetable as the organization of the railway traffic is a complex decision-making problem. The complexity results from the multiplicity of problems and from the number of factors, which should be considered. In the article was described technical-organizational conditioning of the construction of graphic train timetable. We presented mathematical models of the construction of train timetable, in which we took into account-selected boundary conditions. A way of solving a problem was presented also.

3. Technical-organizational conditioning of the construction of the graphic train timetable

The process of the construction of the graphic train timetable is connected with the number of technical-organizational conditioning which it is possible to group into a few issues, i.e.:

1. conditioning associated with elements of the train infrastructure – conditioning generated by elements of the linear and point infrastructure: their state, technical-exploitation characteristics and others,
2. legal conditioning – conditioning forced by provisions, regulations and others prepared on the national level or by the infrastructure manager / of railway undertaking,
3. conditioning connected with superstructure – conditioning associated with the use of means of transport and forced by regulations associated with means of transport, as well as associated with the circulation of traction vehicles,

4. conditioning associated with the railway undertakings – conditioning associated with wishes and demands of railway undertakings resulting from the transport offer which they want to offer for passengers,
5. conditioning associated with the need to implement changes – conditioning coming from observations of linear employees from the realization of the current annual timetable, from changes of the technical equipment of the station and open lines, the technology of the work of railway stations, the work of the depots and other units having at their disposal on traction vehicles, as well as from regulations of allotting of trains paths to the given timetable prepared by the infrastructure manager,
6. conditioning associated with the organization of the railway traffic – works on the graphic timetable should be begin from the section, for which the traffic of trains is greatest, where local work is considerable, and it demanding starting at the section two, three or more pairs of group trains and delivery trains and where is required the biggest using the capacity of the section,
7. conditioning resulting from the priority on the railway network – graphic timetable should be constructed in this way so that trains of permanent running have priority. If on the given section are being carried out transports with high-intensity, it should be pay special attention to the required high capacity of the section, rather than to the constancy of running,
8. conditioning resulting from priorities of pathing of trains on the railway network,
9. conditioning associated with the need for the organization of communication conditions of trains – it should be prepared communication conditions on railway stations of passenger trains with other passenger trains, as well as with means of transport of other branches of the transport.

Every of above issues is complex problem requiring analysis of the multiplicity of aspects. Individual conditioning have a fundamental impact on the journey time of a train on open lines, station time intervals, open lines time intervals and times of stops of trains. On account of the being and the weight of these parameters, it should be pay the particular attention on their value already on the stage of preparing assumptions for construction of the train timetable.

4. The organization of the rail traffic and the formalization of the record of the construction of the graphic train timetable

4.1. General assumptions

Construction of the graphic train timetable in the biggest railway infrastructure manager in Poland (PKP Polskie Linie Kolejowe S.A.) is being carried out using computer support, which all the time is being developed. Railway undertaking, upon completion of works at the stage of the shaping of the transport offer, to start the specific train, a must get from the infrastructure manager timetable. This timetable is being developed by constructors using graphic train timetable on the application filed by the railway undertaking. The railway undertaking is filing applications to the infrastructure manager on individual trains individually. Pathing of trains on the graphic timetable also takes place one by one. It should be seek mathematical methods, which will facilitate works of constructors of the train timetable both on the stage of the shaping of the transport offer as well as the construction of the graphic train timetable, and they will allow for pathing of a few trains simultaneously including boundary conditions in technical-organizational conditioning.

The correct organization of the railway traffic requires constructing the graphic train timetable considering rules of safety, fluidity of the move and expecting of buyers of services in the scope of communication conditions of trains:

1. create graphic timetables for individual routes (it is necessary to define routes independently or to make an assumption that the route of the graphic timetable will agree with the route of the communication line),

2. search on how many graphic timetable should be put train path which is currently being analysed,
3. mark on the graphic(s) timetable model train's path (train's path, for which only a leading hour is taken into account and principles of leading the railway traffic cannot be preserved) (with the help of the A* algorithm); on the graphic timetable it is necessary to mark trains one by one for individual periods of twenty-four hours, in every period it is necessary to consider priorities of pathing of trains on the graphic timetable,
4. check every train marked on the graphic timetable under the angle of the existence of collisions (with the help of the Axis-Aligned Bounding Box algorithm); if a collision is appearing it should be using the Bees algorithm to make correction of laying the path (real pathing); in real pathing it should be observe priorities of trains pathing on the graphic timetable – it is only possible to move train's path of the lower priority.

4.2. Data for the problem

Correct organization of railway traffic, and what is being combined with it, construction of the graphic train timetable requires preparing the respective data. Among them, it should be replaced:

$\boldsymbol{GO}(\boldsymbol{two}) = \langle \boldsymbol{WK.}(\boldsymbol{two}), \boldsymbol{LK}(\boldsymbol{two})\rangle$ – graph of the structure of the railway network showing the route of the graphic timetable *two*,

$\boldsymbol{WK.}(\boldsymbol{two})$ – set of operating control points and forwarding offices (point elements of the railway infrastructure) $wk., wk., wk.' \in \boldsymbol{WK.}(\boldsymbol{two})$ (in addition $wk. = = wk.'$ – when there is stop of the train in the station and $wk. \neq wk.$ – when there is not stop of the train in the station), constituting the route of the graphic timetable *two*,

$\boldsymbol{LK}(\boldsymbol{two})$ – set of connections between operating control points and forwarding offices (linear elements of the railway infrastructure) $elk, elk \in \boldsymbol{LK}(\boldsymbol{two})$, constituting the route of graphic timetable *two*,

$\boldsymbol{KAT}$ – set of numbers of sections of the demand for the transport service $kit, kit \in \boldsymbol{KAT}$ (category of trains),

$\boldsymbol{T_{at}}$ – set of routes (communication lines) t_{hat}, $t_{hat} \in \boldsymbol{T_{hat}}$ individual sections of the demand *kit*,

$\boldsymbol{POCK}(\boldsymbol{t_{hat}})$ – set of numbers of trains *pock*, $pock \in \boldsymbol{POCK}(\boldsymbol{t_{hat}})$, for starting on the route t_{hat},

$go(pock)$ – values of parameters determining leading hours for trains *pock*,

$\boldsymbol{TAR}$ – set of routes *two*, $two \in \boldsymbol{TAR}$, for which the graphic timetable was created,

$\boldsymbol{GR}(\boldsymbol{two}) = \langle \boldsymbol{WRY}(\boldsymbol{two}),\boldsymbol{LB}(\boldsymbol{twr},\boldsymbol{poc})\rangle$ – graph being used for a construction of graphic timetable,

$\boldsymbol{WR}(\boldsymbol{twr})$ – set of numbers of vertexes $wr(twr)$, $wr(twr) \in \boldsymbol{WR}(\boldsymbol{twr})$ showing hours of arrivals and departures on the graphic timetable *twr*, $\boldsymbol{WR}(\boldsymbol{twr}) = = \boldsymbol{WRP}(\boldsymbol{wk},\boldsymbol{twr},\boldsymbol{poc}) \cup \boldsymbol{WRO}(\boldsymbol{wk},\boldsymbol{twr},\boldsymbol{poc})$

$\boldsymbol{WRP}(\boldsymbol{wk},\boldsymbol{twr},\boldsymbol{poc})$ – set of vertexes $wrp(wk,twr,poc)$, $wrp(wk,twr,poc) \in \boldsymbol{WRP}(\boldsymbol{wk},\boldsymbol{twr},\boldsymbol{poc})$ showing moments of trains' *poc* arrivals to the vertexes *wk* on the graphic timetable *twr*,

$\boldsymbol{WRO}(\boldsymbol{wk},\boldsymbol{twr},\boldsymbol{poc})$ – set of vertexes $wro(wk,twr,poc)$, $wro(wk,twr,poc) \in \boldsymbol{WRO}(\boldsymbol{wk},\boldsymbol{twr},\boldsymbol{poc})$ showing moments of trains' *poc* departures to the vertexes *wk* on the graphic timetable *twr*,

$\boldsymbol{LR}(\boldsymbol{wk,wk'},\boldsymbol{twr},\boldsymbol{poc})$ – set of edges $lr(wk,wk',twr,poc)$, $lr(wk,wk',twr,poc) \in \boldsymbol{LR}(\boldsymbol{wk,wk'},\boldsymbol{twr},\boldsymbol{poc})$ indicating the transition of the train *poc* on the graphic timetable

twr associated with the passage between vertexes *wk* and *wk'*,

WRA(***twr***,***poc***) – set of moments of the departure from the first vertex *wra*(*twr*,*poc*), *wra*(*twr*,*poc*) ∈ ***WRA***(***twr***,***poc***) on the graphic timetable *twr*,

WRB(***twr***,***poc***) – set of moments of the arrival to the last vertex *wrb*(*twr*,*poc*), *wrb*(*twr*,*poc*) ∈ ***WRB***(***twr***,***poc***) on the graphic timetable *twr*,

lr(*lk*,*poc*) – values of parameters determining the length of the journey time of trains *poc* along edges *lk*,

lrp(*wk*,*poc*) – values of parameters determining the length of the stop time of trains *poc* in vertexes *wk*,

lrns(*wk*) – values of parameters determining the length of the station time interval in vertexes *wk*,

lrnsz(*lk*,*poc*) – values of parameters determining the length of the open lines time interval for trains *poc* along edges *lk*,

lrsk(*wk*) – values of parameters determining the length of the time required on communication conditions in vertexes *wk*,

t_{rz}(*lr*(*wk*,*wk'*,*twr*,*poc*)) – real durations of states of trains *poc* showing by edges *lr*(*wk*,*wk'*, *twr*,*poc*) on the graphic timetable *twr* between vertexes *wk* and *wk'*,

t_w(*lr*(*wk*,*wk'*,*twr*,*poc*)) – model durations of states of trains *poc* showing by edges *lr*(*wk*,*wk'*, *twr*,*poc*) on the graphic timetable *twr* between vertexes *wk* and *wk'*,

t_{post}(*lr*(*wk*,*wk'*,*twr*,*poc*)) – durations of states of trains *poc* showing by edges *lr*(*wk*,*wk'*,*twr*,*poc*) on the graphic timetable *twr* for operating control points *wk* (in addition *wk* = *wk'*).

4.3. Boundary conditions and indicators of the quality assessment of the solution

Bearing in mind above assumptions construction of the graphic train timetable is a problem consisting in appointing such values of decision variables *y*(*lr*(*wk*,*wk'*,*twr*,*poc*)) written in the form of the vector **Y**(***twr***):

$$\mathbf{Y}(\boldsymbol{twr}) = [y(lr(wk,wk',twr,poc)): y(lr(wk,wk',twr,poc)) \in \{0, 1\}] \tag{1}$$

in addition *y*(*lr*(*wk*,*wk'*,*twr*,*poc*)) = 1 assumes value 1 if given part of the train's *poc* route on the graphic timetable *twr* – *lr*(*wk*,*wk'*,*twr*,*poc*) between two neighbouring vertexes *wk* and *wk'* (in addition vertexes *wk* and *wk'* can have the same number) is appropriate, otherwise *y*(*lr*(*wk*,*wk'*,*twr*,*poc*)) = 0, for which the vector function of the objective assumes minimum values, what it is possible to write:

$$F(\mathbf{Y}(\boldsymbol{twr})) = \left[f_1(\mathbf{Y}(\boldsymbol{twr})), f_2(\mathbf{Y}(\boldsymbol{twr})) \right] \longrightarrow \min, \tag{2}$$

where:

f_1(**Y**(***twr***)) – fragmentary function of the criterion describing the minimization of volumes of differences between the real duration time of given state of the train and the time which doesn't consider principles of correct leading the railway traffic associated with pathing of the given train *poc* in part of route *y*(*lr*(*wk*,*wk'*,*twr*,*poc*)) on the graphic timetable *twr* between two neighbouring vertexes *wk* and *wk'* written with expression:

$$f_1(\mathbf{Y}(\boldsymbol{twr})) = \sum_{\substack{poc \in \\ \in \boldsymbol{POC}(t_{kat})}} \sum_{\substack{lr(wk,wk',twr,poc) \in \\ \in \boldsymbol{LR}(\boldsymbol{wk},\boldsymbol{wk'},\boldsymbol{twr},\boldsymbol{poc})}} p(lr(wk,wk',twr,poc)) \cdot y(lr(wk,wk',twr,poc)) \longrightarrow \min, \tag{3}$$

where *p*(*lr*(*wk*,*wk'*,*twr*,*poc*)) is a value associated with pathing of the given train *poc* along edge *lr*(*wk*,*wk'*,*twr*,*poc*) on the graphic timetable *twr* between two neighbouring vertexes *wk* and *wk'* having interpretation of the difference between the real time t_{rz}(*lr*(*wk*,*wk'*,*twr*,*poc*)) of lasting the state of the given train *poc* showing by given

edge $lr(wk,wk',twr,poc)$ on the graphic timetable twr between two neighbouring vertexes wk and wk' (when there are implemented principles of correct leading the railway traffic), and the model time $t_w(lr(wk,wk',twr,poc))$ of lasting the state of the given train poc showing by given edge $lr(wk,wk',twr,poc)$ on the graphic timetable twr between two neighbouring vertexes wk and wk' (when there are not implemented principles of correct leading the railway traffic) written with expression:

$$p(lr(wk,wk',twr,poc)) = t_w(lr(wk,wk',twr,poc)) - t_{rz}(lr(wk,wk',twr,poc)), \qquad (4)$$

$f_2(\mathbf{Y}(\boldsymbol{twr}))$ – fragmentary function of the criterion describing the minimization of the volume of stop times on operating control points and forwarding offices wk associated with pathing of the given train poc in part of route $y(lr(wk,wk',twr,poc))$ on the graphic timetable twr between two neighbouring vertexes wk and wk' written with expression:

$$f_2(\mathbf{Y}(\boldsymbol{twr})) = \sum_{\substack{poc\in \\ \in \boldsymbol{POC}(t_{kat})}} \sum_{\substack{lr(wk,wk',twr,poc)\in \\ \in \boldsymbol{LR}(\boldsymbol{wk},\boldsymbol{wk'},\boldsymbol{twr},\boldsymbol{poc}): \\ wk=wk'}} t_{post}(lr(wk,wk',twr,poc)) \cdot y(lr(wk,wk',twr,poc)) \longrightarrow \min, \quad (5)$$

It is possible to divide boundary conditions of the issue on resulting from:

1. technical conditioning:
   - initial vertex on graphic timetable twr – $wra(twr,poc)$ (symbolizing the moment of the appearance of the train on the graphic timetable) for each train poc can only have one next vertex,
   - for the intermediate vertex on graphic timetable twr – $wr(twr)$ (symbolizing the moment of the arrival or departure of the train to the specific point on the graphic timetable) for each train poc the number of previous vertexes must be equal to the number of the following vertexes,
   - final vertex on graphic timetable twr – $wrb(twr,poc)$ (symbolizing the moment of the disappearance of the train on the graphic timetable) for each train poc can only have one previous vertex,
2. keeping principles of correct leading the traffic of trains:
   - for each vertex wk the difference between the arrival moment of the next train poc' and the departure moment of train poc must be greater than or equal to the length of the station time spacing $lrns(wk)$,
   - for each vertex wk the departure moment of next train poc' must be greater than or equal to the departure moment of the train poc plus the length of open line time spacing $lrnsz(lk,poc)$ for the edge lk leaving the vertex wk,
   - for each vertex wk which are places where trains can terminate and begin running, the difference between the departure moment of the next train poc' – $wra(twr,poc')$ and the arrival moment of the train poc – $wrb(twr,poc)$ should be greater than or equal to that of the vertex wk – $lrsk(wk)$.

5. Summary and conclusions

Proper organization of the railway traffic is a complex decision-making problem. How we indicated in the article it is being determined with proper construction of the graphic train timetable. The construction of the train timetable is a process, which can on leading the correct traffic organization – in accordance with rules of safety and resulting from control command and signalling rule of leading the traffic of trains on the railway network.

For correct preparing of the graphic timetable, it is necessary to use technologically advanced tools. It requires on one hand the acquaintance of principles of leading of the movement, technical and technological conditioning, control command and signalling safety and on the other hand

expectations of future users. Introduced in outline mathematical model allows for pathing of trains on the graphic timetable in compliance with priorities of pathing.

As the evaluation criterion of solution quality was applied a minimization of values of differences between the real time of lasting the given state of train (ride or stop), and with model time (when there are not implemented principles of correct leading the railway traffic connected with pathing of the train along the given railway line). The model is taking into account all defined technical-organizational conditioning.

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