Grzegorz PAWLAK
Poznan University of Technology

MODEL SYMULACYJNY PROBLEMU CYKLICZNEGO SZEREGOWANIA POCIAGÓW NA LINII JEDNOTOROWEJ

Streszczenie. Rozważany problem dotyczy dwukierunkowej jednotorowej linii kolejowej. Naturalnie jednotorowa linia kolejowa powoduje to, że pociągi podróżujące w obu kierunkach muszą się wymijać i zatrzymywać na stacji. Każda stacja ma ograniczoną przepustowość, określoną pojemność definiującą ile pociągów w danym momencie może się na niej znajdować. Celem pracy jest określenie cyklicznego harmonogramu z maksymalizacją pociągów dla danych parametrów linii kolejowej to znaczy liczby stacji, pojemności tych stacji oraz czasu przejazdu pomiędzy poszczególnymi stacjami. Metody optymalizacji oparte na symulacji służą do znalezienia cyklicznego uszeregowania pociagów, z jednej strony wykorzystującego maksymalną przepustowość linii w obu kierunkach, a z drugiej respektującego ograniczenia dotyczące czasów przejadów pomiędzy stacjami, jaki i pojemności tych stacji. Na koniec można zbudować model symulacyjny automatycznego generowania rozkładów jazdy, uwzględniający schematy planowania cyklicznego ruchu pociągow i określić horyzont czasowy takiego cyklu.

CYCLIC SINGLE TRACK RAILWAY SCHEDULING PROBLEM BY SIMULATION

Summary. Considered problem involves a single-track railway line that connects multiple stations. Trains can travel in both directions along the track, but since there's only one track, they must wait for avoiding collisions and deadlocks. The objective of the scheduling problem is to determine the cyclic schedule with trains maximization for the given set of the railway parameters like stations capacity and traveling time between them. Simulation-based optimization methods use to simulate train movements for the particular line and stations capacities. Optimization algorithms are then used to find the effective schedule based on the simulation results. In this paper, the case of models of STRSP are considered and analyzing them from both the station capacity point of view and the maximal number of trains that can be scheduled for the given single-track railway lines. Finally, one can construct a simulation model that automatically generates timetables for trains, including cyclic train scheduling cases in the minimum cycle time horizon.

1. Introduction

The motivation for research on the single track scheduling problem often comes from real-world applications. Such as the transportation of coal from mines to a harbor in the case of the Australian railway as a practical example. Therefore, finding optimal solutions to the single track scheduling problem is an important research topic with practical implications. The increasing demand for iron ore or coal forces practitioners and researchers to find more effective train network transporting for goods from the mains to the harbor [4]. For the quite old railway infrastructure with single line tracks increase transport efficiency it is a challenge. Then, the goal is to find the maximum number of the trains traveling in both directions. From the one side the effective solution assumes to solve the trains scheduling problem, on the other hand the practical application require the cyclic timetable in the specified time horizon. The time table form a kind of the train traveling "patterns" dependent on the lines parameters such as the number of stations in the line, the stations capacities and the traveling times between the stations.

The classical Single Track Railway Scheduling Problem (STRSP) is largely elaborated in the literature. The research are conducted in the area for a long time. One of the first results on the subject was presented by Szpigel in [5]. The problem arises when a set of trains need to travel along a single track with limited stations capacity. It is complicated by the fact that trains traveling in opposite directions cannot pass each other, and the number of trains that can be accommodated at each station is limited by the station's capacity. For the general case, the problem is NP-hard, from the complexity point of view.

One can distinguish the two ways of the modeling and solving such a problems. First to construct dedicated solutions adjusted to the particular lines and local circumstances. This approach requires considering many detailed parameters and constructed solution could be effective but for the static system and very specific dedicated assumptions. Such a solutions are vulnerable for the small changes and do hardly construct robust methods. Moreover, it requires continuous and constant customization. Usually, they give the accurate results but with significant runtime of the algorithms. The example of the efficient scheduling of trains on a single track with limited stations capacity is crucial for the safe and reliable operation of railway systems. The problem has applications in various fields, including transportation, logistics, and supply chain management. As a result, there is a literature on the single track scheduling problem, including various algorithms and models for solving it [2]. In practice, there are many factors that need to be taken into account when scheduling trains for transporting goods, such as the capacity of the stations, the speed and weight of the trains, the availability of tracks, the weather conditions, and the safety and reliability of the system [6]. To solve the classical single track scheduling problem, various optimization techniques can be used, such as mathematical programming, simulation, or heuristics. The optimal solution depends on the specific constraints and objectives of the problem, such as minimizing travel time, maximizing train throughput, or ensuring safety and reliability [4, 2, 6].

On the other hand the most general models are considered for the more dynamic systems, where the environment is changing. One can find the limitations of the particular railway lines. Moreover, the practically interested problem can be formulated, for example,as to change the line by infrastructure modifications and investments. A key factor in the problem is the maximum throughput rate, which is the maximum number of trains that can pass through a stations for the particular time horizon. This rate is limited by the station's capacity and the speed of the trains, among other factors. The scheduling efficiency of the system depends on how well the maximum throughput rate, for the given cycle time, is utilized.

Then the simulation technique that uses computer models to simulate an operations of the railway system and evaluate different scheduling scenarios. Simulation can provide parameters and insights into system performance and help identify potential bottlenecks and improvements for dynamic and varying environment.

The paper considers some models and formulates capacity station dependencies. The approach considers the "topology" of the single railway line defined as: the train capacity in the stations, the number of the stations in the line and the distances between them. Then the interesting problem is the maximization of the trains traveling in both directions and construction of the cyclic timetable. The results can be utilized for practical "what-if" analysis, where the lines are described by the number of stations, total travel time, and travel time between stations. The changes on the line and train parameters may cause the bottlenecks which should be avoided and the estimation of the maximum trains traveling in the cycle scheduling for the given time horizon.

2. Problem Formulation and Models

We are attempting to determine the maximum number of trains that can travel from the starting station to the ending station and back within a given time frame. That number can be treat as an upper bound of the train number for the general case. Let us define:

T_s as the time at which the first train begins its journey. T_f as the time at which the last train completes its journey. We will be examining journeys that take place within the time interval $[T_s, T_f]$, subject to the following assumptions:

- The time taken to travel between neighboring stations is constant and is denoted by $t_{i,j}$.
- It is possible for at least one train to travel between any two stations within a given time.
- The start station (s) and the end station (e) have infinite capacity, denoted by cp_s and cp_e respectively.

2.1. Train maximization problem

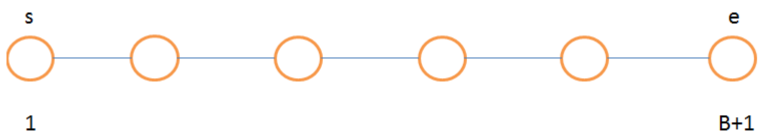
One can define the following:

B - the length of the railway from the starting station to the ending station. There are a total of $B+1$ stations, including the starting and ending stations. Hence, the ending station is denoted by $e = B + 1$.

T - the length of the time interval being considered, where $T = T_f - T_s$.

there are interested to finding $maxR_{(B,T)}$, which is the maximum number of trains that can travel the distance B within the given time T.

There may be generated several models for the same physical railway system. The travel times can differ, for example, by applied maintenance cases and potential



Rys. 1. Single line model

changes in the station capacity (considered investments). The station capacity it is the maximum number of trains which could be accommodated by the particular station. For a single track line that parameter specifies the fact that the trains can cross traveling in opposite directions and defines the number of trains circulating in the system. In the terminus cases if for all stations the $cp_i = 1$, form the line where the trains can travel only in one direction from source to final station (for both the train capacity is infinite) and then all traveling back. On the other hand, if all capacities are infinite (not used in practical case) then trains can cross on each stations cf. Fig. 1.

2.2. Minimization of the total traveling time model with finite capacities

This model aims to minimize the total traveling time subject to finite capacities at each station.

Under above assumptions, one can formulate the following objective function for the particular model as a calculated sub-problem:

$$\min_{n_{i,j}} \sum_{i=1}^{e-1} \sum_{j=i+1}^{e} n_{i,j}(t_{i,j} + t_{j,i}) \tag{1}$$

This function minimizes the total traveling time of all trains on the railway. The variables are the number of trains n traveling between each pair of stations (i, j) with capacity constraints the number of trains arriving at any station i cannot exceed its capacity cp_i, where $i = 1, 2, \ldots, e$. For the possible stations' capacity changes the total completion times can be represented as:

$$\sum_{j=1}^{i-1} n_{j,i} - \sum_{j=i+1}^{e} n_{i,j} \leqslant cp_i, \qquad i = 1, 2, \ldots, e \tag{2}$$

These constraints ensure that the number of trains traveling between each pair of stations does not exceed their capacity, and the total time taken by all trains does not exceed the time interval T.

Station capacity dependencies can be formulated as follows:

cp_i: the capacity of intermediate station i (i.e., the maximum number of trains that can be on the station at the same time), which is assumed to be finite. Our objective is to find the minimal cp_i for each station $i \in 2, 3, \ldots, e-1$ that allows the maximum number of trains to pass through within the given time.

The greedy strategy that gives always priority to the train that goes first, causing delays 0, 1, 2... respectively to the following trains provides such upper bound. One is able to present patterns that results with a sum of times equal to this bound or lower.

Let's denote:

t_{s_i} –time train i departures from starting station s, $t_{s_i} \in \{0, 1...\}$;

t_{f_i} – time train i reaches back the station s,
so $c_i = t_{f_i} - t_{s_i}$.
We can observe differences in t_{s_i} between these patterns.
$t_{s_i} = i$ for $i < B$ and $t_{s_i} = 2(i-1)+1$ for $i \geqslant B$;
whereas:
$t_{s_i} = i$,
but in both cases $t_{f_i} = 2B + 2(i-1)$ and $c_i \leqslant 2B + i - 1$.

Note that any additional wait of the first train enlarges $\sum_{j=1}^{R} c_j$ (as it enlarges t_{f_i} for some i, without changing t_{s_i}).

It can be observe in the pattern presented below, that results with:

$$\min_j \sum_{j=1}^{R} c_j^{(3)} \leqslant \min_j \sum_{j=1}^{R} c_j^{(2)} \leqslant \min_j \sum_{j=1}^{R} c_j \qquad (3)$$

The consequences are that one can expect that the higher capacity of the stations can shorten the cycle of the trains traveling. Later the simulation shows that the bottlenecks in the trains capacity and traveling times between stations can be crucial to achieve the effective cyclic trains timetable.

3. Algorithmic Simulation Model

In order to implement a simulation algorithmic solution for the models described above, it is necessary to address the bottleneck problem. There are several methods to avoid bottlenecks, the one is chosen as to reserve at least one unit of capacity on stations where the capacity is greater than one.

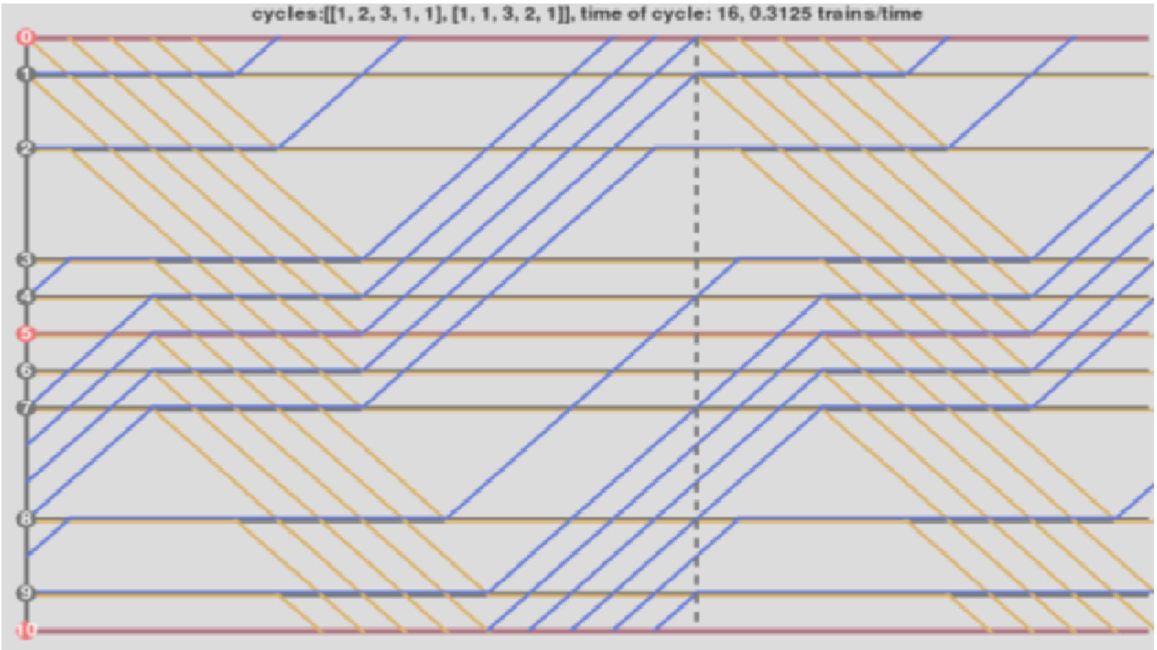
Stations with a capacity equal to one can be effectively reduced from the line, and the travel times in neighboring stations with capacities greater than one are increased accordingly.

The simulation then calculates a feasible solution and generates a cyclic timetable for the trains.

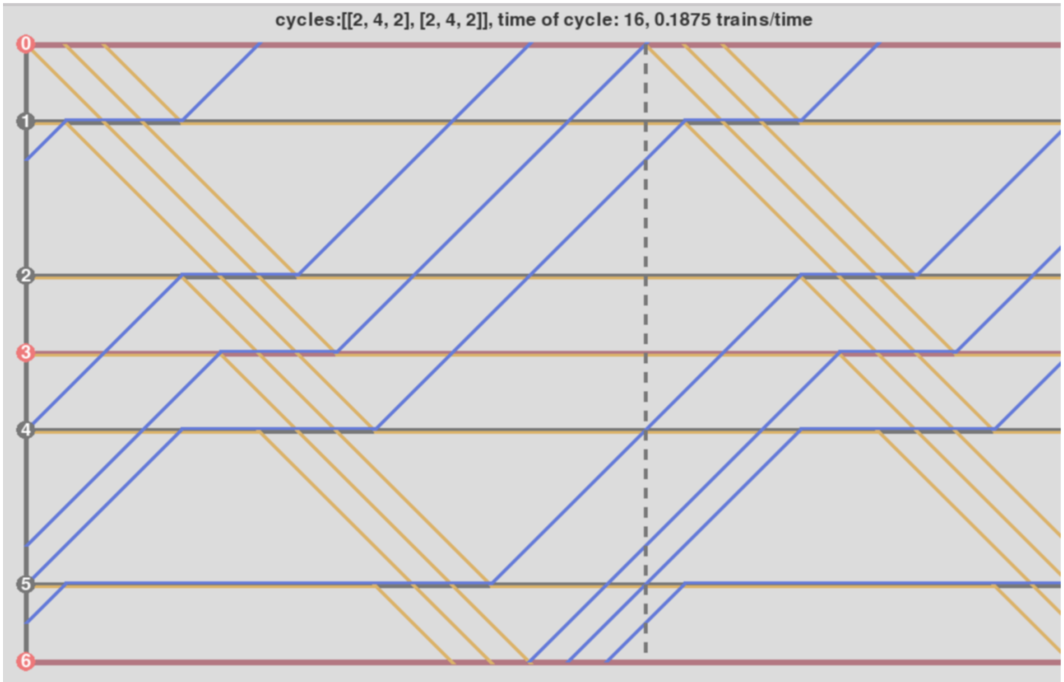
The algorithm takes also into account potential collisions and conflicts in the trains traffic. The all possible collisions in such a system where described previously in literature [3] and where implemented to the simulator. In the system in all lines where applied an integer values of travel times.

The algorithm generates an effective cyclic train timetable, as illustrated in the examples in Fig. 2 and 3. To perform a WHAT-IF analysis, one can manipulate the stations capacity parameter and the traveling times, to determine the optimal increase in capacity for a given instance of the railway line. The software simulation package was prepared in [1] and several experiments were performed.

On the Fig. 2 and Fig. 3 on the vertical axis there is the single line definition instance with the stations and travel time units between them. Because trains travel in both directions there mirroring the stations with the end of the line as a pivot. The trains journey is depicted in the line where horizontal lines identifies the stations and time units is running on axis X. In the Fig. 2 the five stations line was shown with a travel times $[1, 2, 3, 1, 1]$ respectively, the total cycle time in that case was equal to 16 and the theoretical trains density in the line was calculated as $0,315$. One can observe the pattern



Rys. 2. Example of time-table solution produced by the simulation.



Rys. 3. Example of time-table solution produced by the simulation.

in the time table after 16 time units the time table is repeating and the continuous cyclic train scheduling was constructed. For this particular case there is the optimal cycle.

Similarly, there is shown the second example see Fig. 3 where the line consists four stations with a travel times $[2, 4, 2]$ respectively, with the total cycle time also equal to 16. One can observe that the traffic in that example is less dense so the density parameter is equal to $0, 1875$ trains for a time. Adequate to the previous example, the cyclic train schedule was constructed.

4. Conclusions

Overall, the single track train scheduling problem with limited station capacity is a complex optimization problem that requires careful consideration of many factors, including train speeds (caused for example by the maintenance), stations capacities, and safety constraints. By using appropriate optimization techniques, it is possible to find an optimal solution that minimizes travel time while cycle time and efficient train operations.

The simulation algorithmic model generating the effective cyclic time-tables had been presented. The simulations models can identify the single track railway lines limitations and potential bottlenecks in relatively easy and fast way. Moreover, the methods could be used for the very speculative WHAT-IF analysis for many alternatives.

Having such a tool one can easy perform and evaluate the several tests for the practical cases. Then it is not difficult to get the general picture of the train transportation system with the structural limitations of the particular lines. The achieved simulations results can be also used for the preprocessing or bounding parameters for the more sophisticated methods and models.

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