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Abstract. We present a track-choice and vehicle scheduling extension of the commonly known method for the generation of periodic event schedules ‘PESP’. The extension makes use of the mesoscopic track infrastructure representation widely used by public transport planners and operators. Taking into consideration the technical and operational constraints given by rolling stock, station and track topology data on the one hand, and the commercial requirements defined by a given line concept on the other, the method presented generates periodic timetables including train-track assignments. Due to the utilization of infrastructure based track capacities, we are also able to assess the feasibility of the line concept given. Additionally, the method allows for handling temporary resource restrictions (e.g. caused by construction sites or operational disturbances) up to a certain degree.

Keywords: Periodic Event Scheduling Problem, Mesoscopic railway topology, Service Intention, Track Choice

1 Introduction

In the operational management of railway networks, an important requirement is the fast adaptation of timetable scenarios, in which operational disruptions or time windows with temporary unavailability of infrastructure, for instance during maintenance time windows, are taken into account. In those situations, easy and fast reconfiguration and recalculation of timetable data is of central importance. This local and temporal rescheduling results in shifted departure and arrival times and sometimes even in modified stop patterns at intermediate stations of train runs. In order to generate reliable timetabling results it is a prerequisite that train-track assignments, as well as operational and commercial dependencies are taken into consideration and that all these dependencies are not conflicting with each other. Hence, finding the right level of detail for modelling track infrastructure and train dynamics is crucial for supporting the planning process in an optimal way. This requirement motivated several research groups to combine common timetabling procedures with constraints resulting from mesoscopic infrastructure information in recent years.

From the existing approaches, we will discuss below some that are relevant to our work. Hansen and Pachl [6] show how running, dwell and headway times at critical route nodes and platform tracks must be taken into account for train processing and present a deep timetable quality analysis depending on these parameters. De Fabris et al. [4] calculate arrival and departure time, platform and the route in stations and junctions that trains visit along their lines. Bešinović et al. [1] present a micro–macro framework based on an integrated iterative approach for computing a microscopically conflict-free timetable that uses a macroscopic optimization model with a post-processing robustness evaluation. Caimi et al. [3] extend PESP (see e.g. [7]) by proposing the flexible periodic event scheduling problem (FPESP), where intervals are generated instead of fixed event times. By applying FPESP, the output does not define a final timetable but an input for finding a feasible timetable on a microscopic level, ([2] and [3]).

Our modelling approach is also based on an extension of PESP and takes the service intention (SI) as input data structure. The SI was first described in Caimi [2] and integrates commercial timetabling requirements given by the respective line concept on one side and technical constraints on the other. It largely corresponds to the 'line concept', and represents functional timetabling requirements including line data, line frequencies and separations as well as line transfers at specific stations. Similarly to de Fabris et al. [4], we call this level of abstraction of the available resources 'mesoscopic topology'. Together with the functional requirements of the SI this mesoscopic infrastructure data model of a given scenario is entered into a standard timetable editor (see, e.g. SMA Viriato, [8]).

2 Methodology

The investigation of feasible event times for individual train runs and the corresponding resource allocations fitting into an integrated clock face timetable is usually done manually in a time consuming way. On the other hand, algorithmic approaches for solving this task computationally require models based on microscopic information about track capacity. This capacity information can be aggregated to headway constraints that are used for solving standard periodic timetable problems. In order to facilitate this step, we present a generic approach, which makes use of the mesoscopic infrastructure. We call this approach Track-Choice PESP (TCPESP), as it can be considered as an extension of PESP, which includes the selection of relevant headway constraints into the optimization problem.

The SI is defined by a set of train runs. Each train run belongs to a line L and is characterized by the sequence of sections that are traversed and a corresponding time interval, which is required for either running or stopping on a corresponding track section. Each time interval has a minimal and maximal value. Stop nodes typically provide a service for boarding or de-boarding. Together, a pair of train runs moving in opposite directions makes up a train circulation.

In the TCPESP model, the mesoscopic infrastructure consisting of sections is summarized as a set I of operation points. Operation points are largely tracks and stations but can also be other critical resources as junctions (see example below). As mentioned before, each operation point $i \in I$ is associated to a capacity consisting of a set of tracks T_i. A train run $l \in L$ is described by a sequence of operation points of I.

Based on our mesoscopic model we form an event-activity network (E, A). The set E of events consists of an arrival event arr_{li} and a departure event dep_{li} for each train run $l \in L$ and operation point $i \in l$. The activities $a \in A$ are directed arcs from $E \times E$ and describe the dependencies between the events. For every train run we have arcs between arrival and departure events at the same operation points (dwell times or trip times) and arcs between departure and arrival events of successive operation points (time needed for the travel between operation points). Further arcs include connections between train runs, headways and turnaround operations (see section 3). We refer to [7] for a detailed overview of the modelling options of dependencies. Fig. 1 provides a sample of such an event graph.

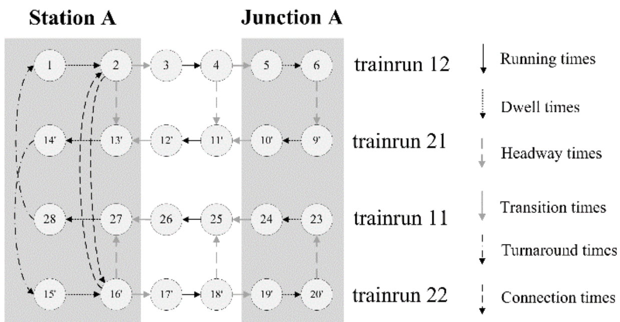

Fig. 1 Sample of an event activity network, where arcs connect arrival and departure events. Nodes belonging to grey shaded boxes indicate events at operation point type operation points. Other nodes indicate track type arrival and departure events. Arrow line styles indicate different types of time dependencies.

Headway arcs $a \in A_H$ are especially important for explaining the 'track-choice PESP model' below. Headway arcs are used to model safety distances between trains running in the same and in opposite directions (see example in Fig. 1). For the sake of simplicity we consider in TCPESP (1) below only headways related to one operation point, i.e. we omit headways for train runs in opposite directions over several successive operation points. The problem formulation (1) can be easily extended to include general headways.

The classical PESP tries to determine a periodic schedule on the macroscopic level (i.e. without using the tracks at an operation point) within a period T. Event $e \in E$ takes place at time $\pi_e \in [0, T)$. The schedule is periodic with time T, hence each event is repeated periodically $\{\dots, \pi_e - T, \pi_e, \pi_e + T, \pi_e + 2T, \dots\}$.

The choices of the event times π_e depend on each other. The dependencies are described by arcs $a = (e, f)$ in A and modeled as constraints in the PESP. The constraints always concern the two events e and f and define the minimum and maximum periodic time difference l_a and u_a between them. These bounds are given as parameters in the PESP model. We therefore look for the event times π_e for every $e \in E$ that fulfill all constraints of the form

$$l_a \leq \pi_e - \pi_f + p_a T \leq u_a, \text{ for all } a = (f, e) \in A, \quad (1)$$

where p_a is an integer variable that allows the constraints of the form (2) to be met in a periodic sense.

Track-choice PESP model. We extended the classical PESP model by using the number of tracks T_i at each operation point $i \in I$. The track-choice PESP model assigns the arrival event arr_{li} and the departure event dep_{li} of train run l at operation point i uniquely to a track in T_i. We can use these assignments to switch on headway arcs $a \in A_H$ by using the following big-M-approach. In addition to variables π and p from the classical PESP model we need: (i) Binary variables tc_{et} (track choice) for each event $e \in E$ and track $t \in T_{i(e)}$, where operation point $i(e)$ is associated to event e, i.e. e is equal to arr_{li} or dep_{li} for a train run l. (ii) Binary variables h_a for every headway edge $a = (f, e) \in A_H$. Headway edges are always between events at the same operation point, therefore $T_{i(e)} = T_{i(f)}$ holds. The track-choice model is defined by:

$$\min f(\pi, p)$$

$$\begin{aligned}
s.t. \quad & l_a \leq \pi_e - \pi_f + p_a T \leq u_a, && \forall\ a = (f, e) \in A \setminus A_H, && (1)\\
& l_a - (1 - h_a)M \leq \pi_e - \pi_f + p_a T \leq u_a + (1 - h_a)M, && \forall\ a = (f, e) \in A_H, && (2)\\
& \textstyle\sum_{t \in T_{i(e)}} tc_{et} = 1, && \forall\ e \in E, && (3)\\
& tc_{arr_{li}t} = tc_{dep_{li}t}, && \forall\ l \in L, i \in l,\ t \in T_i, && (4)\\
& h_a \geq tc_{et} + tc_{ft} - 1, && \forall\ a = (f, e) \in A_H,\ t \in T_{i(e)} && (5)\\
& tc_{et}, h_a \in \{0,1\}, \pi_e \in [0, T), p_a \in \mathbb{Z}, && \forall\ e \in E, t \in T_{i(e)}, a \in A,
\end{aligned}$$

where M is a big enough natural number.
There are many different objective functions $f(\pi, p)$ described in literature [7]. In our test case below we minimize the total passenger travel time. In (1) are the normal PESP constraints summarized (without headway arcs). In (2) are the headway constraints, which can be switched off with a big-M technique. The assignment of the events to the tracks is done in (3). (4) is used to assign the corresponding arrival and departure events to the same track. In (5) the headway variable is set to 1, if the events take place on the same track, i.e. the headway is required at this operation point.

3 Case study

In order to validate the proposed TCPESP model we designed a simple test case. The relationship between the macroscopic timetable events of three train lines are illustrated by means of a simplified network graph (see Fig. 2a). To validate the model, a virtual railway network was defined for which the service intention was implemented (see Fig. 2b).

The test network contains the two main station nodes (Station A and Station B) connected by line 2, and three stop stations, Stop A, Stop AT (served by line 1) and Stop BT (served by line 3). The planning-relevant secondary conditions for the case study are limited to stations A and B. The period of each train run is indicated in Table 1.

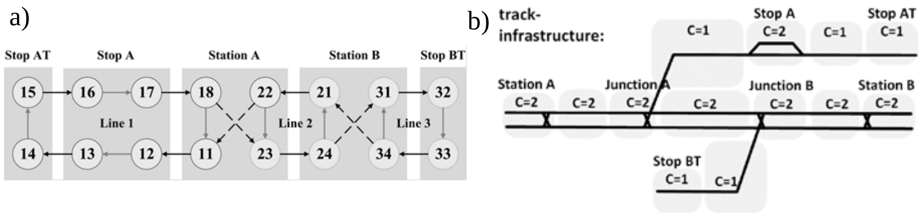

Fig. 2. a) Schedule activity network with commercial dependencies modified from Goverde. Line 1, serving Stop A and Stop AT and connecting to Line 2 in Station A. Line 2 connecting Stations A and B. Line 3, serving Stop BT and connecting to Line 2 in Station B. b) Track infrastructure of the test scenario with an indication of track capacities at each operation point. Operation points indicated as grey shaded boxes.

Fig. 2a shows the service intention including train lines and commercial dependencies between single train runs of each line. Table 1 below provides an example of constraints related to the hourly service of line 2 running from station A (St A) to station B (St B). Fig. 2b shows the track infrastructure of the scenario together with the mesoscopic section topology indicating the section capacities by the corresponding number of horizontal lines.

The SI of test case A offers an hourly service of line 2 between major Stations A and B with connections to and from line 1 in station A and to and from line 3 in station B. A complete rotation of line 1 and 2 takes 120 minutes, one of line 3 takes 60 minutes. Therefore two vehicles are needed for rotations of line 1 and 2 and one is needed for line 3. Line services with train runs and corresponding periodicity and minimum circulation times are indicated in Table 1.

Table 1. Line services with minimal trip times and periods. Odd numbers indicate train runs in one direction; even numbers indicate train runs of the same line in the opposite direction.

Line ID	Service ID	Minimum trip time	Period
1	11	50	60
1	12	50	60
1	13	50	60
1	14	50	60
2	21	50	60
2	22	50	60

Line ID	Service ID	Minimum trip time	Period
2	23	50	60
2	24	50	60
3	31	20	60
3	31	20	60
3	32	20	60
3	32	20	60

Fig. 3 illustrates the results of the TCPESP algorithm for the given test scenario. In addition to the output of the conventional PESP algorithm given by arrival and departure event times, the result that we obtain from the TCPESP model includes track assignment information for each train run. The rail infrastructure of the test scenario consists of two single-track lines (line 1 and 3) and one double track line (line 2). We indicate the resulting track assignment by track numbers (T1 and T2) to each train run during run time on a given track section (see track diagram above each line diagram). There, the number of grey bold horizontal lines is identical to the number of tracks available at a corresponding operation points (T1 or both T1 and T2, respectively). From Fig. 3 it can be seen that the TCPESP algorithm only permits contra rotating train runs to meet in double track sections (line 1) and connecting train runs to meet in a station on neighboring tracks (platforms; St A: line 1 and 2, St B: line 2 and 3). Line styles correspond to directed train runs in both, the track diagrams and the time diagrams.

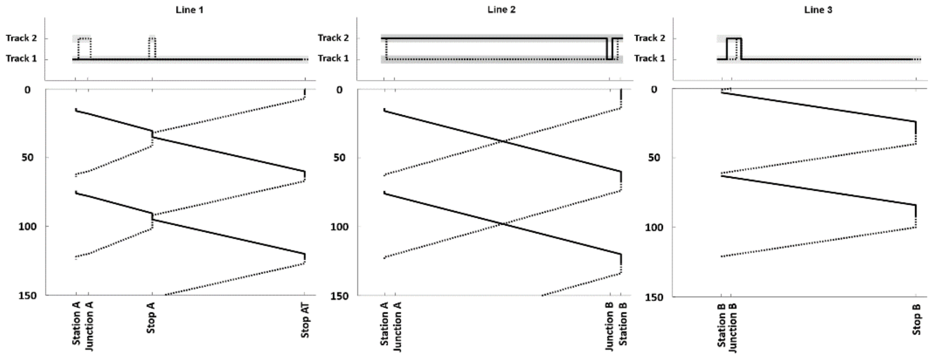

Fig. 3 Scheduling results obtained from of our TCPESP model. A train diagram with the arrival and departure event times is plotted together with the track assignment. Vertical axis: time between 0 and 150 minutes, horizontal axis: sequential locations. St A: station A, St B: station B, Stp A: Stop A, Stp AT: Final stop at AT. T1 and T2 with grey shaded horizontal lines above each location-time diagram indicate track assignments for each vehicle circulation of the three given lines.

4 Discussion and outlook

We introduced and successfully applied the new timetabling model TCPESP, which can be used to support timetable planners for generating train and vehicle schedules with track assignment. This model is based on an extension of the well-known PESP model and can be configured by using a standard schedule editor. Future developments include (i) the generation of the SI using a standard line planning method (see e.g. [5]); (ii) the evaluation of timetable stability. In that way, we expect to further improve the quality of TCPESP results and contribute for speeding up and facilitating practical railway timetabling.

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