Solving Train Timetabling Adjustment Problems with integrated track assignments

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1 INTRODUCTION

The growing reliance on rail transportation in contemporary society drives the need for maintenance and hence increases the number of construction sites on the railway network. Consequently, railway tracks are either partially or fully possessed, potentially leading to the infeasibility of the basic hour pattern (BHP), i.e., a fixed-duration cyclic timetable that is repeated throughout the day and is typically constructed by solving the Train Timetabling Problem (TTP). Consequently, an alternative hour pattern (AHP) is designed such that the impact of construction works on the service quality is minimised. This modification process, or the Train Timetabling Adjustment Problem (TTAP) introduced in Van Aken *et al.* (2017a), becomes even more complicated when safety restrictions and subsequent planning stages in railway systems are involved.

Most TTAP studies are based on the macroscopic models designed for the TTP, where locations serve as nodes and the tracks connecting them are arcs. These models typically use the Periodic Event Scheduling Problem (PESP) (Serafini & Ukovich, 1989), which has laid the foundation for many cyclic timetabling projects including the work in Liebchen (2008) that generates the first optimised railway timetable in practice. Nonetheless, these models do not guarantee feasible in-station routes when construction works do not occupy the entire station (Van Aken *et al.*, 2017a). In contrast, a microscopic modelling approach can ensure feasibility, but it leads to immense mathematical models due to the countless details of the railway network.

Lamorgese *et al.* (2017) propose to solve the TTP with an exact model based on a micro-macro iterative approach: a macroscopic timetable is generated and then fed into a microscopic one to find a feasible schedule, and this process is repeated with added extra restrictions if the second phase faces infeasibility. Alternatively, the infrastructure can be modelled at a mesoscopic level to incorporate more details while maintaining the mathematical model at a solvable size. Wüst *et al.* (2019) develop a track-choice approach to generate cyclic timetables and track assignments, which is then extended by Masing *et al.* (2023) to integrate in-station routing.

This study aims to tackle a variant of the TTAP in which track assignments are incorporated and the measurements consist of train retiming, reordering, cancelling, and short-turning. By making use of a mesoscopic topology that specifies in-station and open tracks (i.e., the tracks in and between stations, respectively), we extend the standard event-activity network and integrate the selection of tracks for each arrival and departure. To solve the extended TTAP, we use a Mixed Integer Linear Programming (MILP) approach that is based on the PESP and evaluate the performance of our model on large-scale real-life instances.

The contribution of our study is as follows. The extended network allows us to model train short-turning directly rather than doing so via a separate procedure as in previous studies: Van Aken *et al.* (2017a) use a pre-processing module to make short-turning decisions which are later fed into their TTAP model. The authors later extend their work by proposing two different strategies for short-turning trains in Van Aken *et al.* (2017b) and state that future research could attempt integrating short-turning into the TTAP model. The modelling approach used in this paper is based on the work of Wüst *et al.* (2019) and Masing *et al.* (2023). However, both studies limit the models to only choosing in-station tracks. We further expand the network such that open tracks are assigned directly in the model. Infrastructure capacity is also addressed via track assignment - a different approach from existing literature that typically uses a separate set of constraints accounting for the (reduced) number of tracks. Consequently, we can address partial open track possessions, a scenario that is often neglected in previous studies in the scope of maintenance possessions (Van Aken *et al.*, 2017a,b) but is more difficult to handle due to the generation of extra headway restrictions.

2 METHODOLOGY

In the macroscopic modelling approach of the TTP and TTAP, train stations and service points are modelled as nodes and the arcs connecting them are open tracks between locations. To integrate track assignments, we use a mesoscopic topology and extend the standard event-activity network (EAN) commonly used in timetabling problems. Platform and non-platform tracks within the locations are considered nodes. For open tracks, we take into account different driving routes to travel from one station to another.

We illustrate the construction of an extended network using an example as in Figure 1, in which a service departs from station X, drives to and dwells at station Y, and finally arrives at station Z. Each station consists of two platform tracks ($l_t, l \in \{X, Y, Z\}, t \in \{1, 2\}$), and there are two open tracks directly connecting X to Y, and Y to Z ($r_t, r \in \{XY, YZ\}, t \in \{1, 2\}$). In the extended network, each arrival event is associated with an in-station track, whereas a departure event is defined by both a track and a driving route.

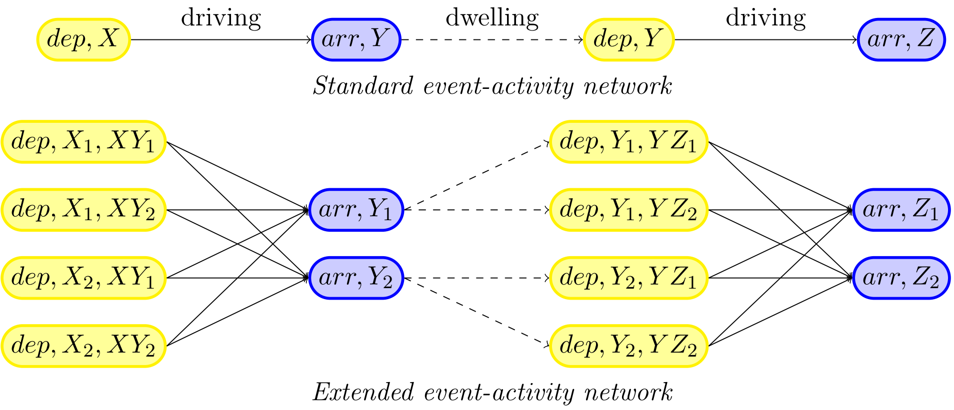

Figure 1 – *Example of an extended EAN. Yellow (resp. blue) nodes represent departure (resp. arrival) events. Solid (resp. dashed) arrows represent driving (resp. dwelling) activities.*

Consequently, the activities are also duplicated: There are eight driving activities from X to Y based on the platform tracks at both locations and the driving routes connecting them, and at most one activity should be selected. For dwelling activity, we only allow for departing from the same track as the preceding arrival event (i.e., trains cannot depart from platform Y_2 if they arrive at platform Y_1, and vice versa).

This modelling approach allows us to integrate short-turning decisions directly by adding *short-turning activities*. Taking the service illustrated in Figure 1 as an example, if there is complete possession between stations Y and Z, we can add a short turning activity connecting one of the arrival events at Y to a departure event from Y of a different service. Such activities can be added based on additional restrictions, e.g., a short-turning activity is included if the rolling stock used for the prior service is compatible with the subsequent one.

To solve the TTAP with integrated track assignments, we use a MILP model that extends the Periodic Event Scheduling Problem (PESP)-based formulation proposed in Van Aken *et al.* (2017a), who introduce the cancellation, retiming, and reordering variables that modify the timetable. The objective is to minimise the number of cancelled events and total deviation of event times in minutes. When events are cancelled, we deactivate the PESP constraints corresponding to the activities with which these events are incident. To account for track assignments, we use a set of track-choice variables representing the selection of tracks as in Wüst *et al.* (2019). Consequently, the PESP constraints of headway and turnaround activities on certain tracks should also be deactivated when they are not chosen. For example, if two trains drive on different routes that do not share any common open tracks, the headway restriction between them is considered irrelevant.

3 RESULTS & DISCUSSION

To evaluate the performance of our proposed TTAP model, we construct real-life instances using data from Netherlands Railways, the principal railway operator in the Netherlands that spans most of the country and operates cyclic timetables with a cycle period of 60 minutes. We select the Randstad metropolitan area which contains the four largest Dutch cities and involves 205 locations, 832 in-station tracks, and 626 open tracks. During a weekend hour, 174 train services run through this area, accounting for 63% of the total number of services. The corresponding extended EAN when no possessions take place consists of 34230 events and 148713 activities, which are significantly higher than in the standard network (5448 events and 19390 activities).

Table 1 presents our three possession cases which are selected arbitrarily from the ten busiest locations and connections. We focus on partial possessions as this type leads to an increase in headway restrictions and therefore is more challenging to handle. Using Java to implement the TTAP model with integrated track assignments and short-turning, we set the penalty of cancellation to be 100 per event and that of delaying (resp. advancing) to be 1 (resp. 2) per minute. The instances are solved to optimality using the commercial solver IBM CPLEX 22.1.1.

Table 1 – *Possession cases. The second (resp. third) column defines the possessed in-station (resp. open) tracks for each case (e.g., "Asb: 4/6" means that four out of six tracks at Asb are possessed, and "Hfd-Shl: 2/4" means that two out of four open tracks between Hfd and Shl are possessed). The last column specifies the number of additional headway restrictions generated due to the reduced number of tracks.*

Case	In-station possession	Open-track possession	# additional headway
1	Asb: 4/6		872
2		Hfd-Shl: 2/4	924
3	Ledn: 6/10; Rtd: 9/13; Ut: 10/21	Ut-Utvr: 6/8; Utvr-Utza: 2/4; Utvr-Utln: 2/4; Ashd-Asb: 2/4	3462

Table 2 shows the numerical results for each case. We observe that there are no cancelled events for all instances. This is likely because our cases do not involve complete possessions and our model allows for flexible routing of trains in which only relevant headway and turnaround constraints are considered. Delaying occurs more frequently than advancing event times due to our choice of penalty values, and the proportion of events that are retimed is relatively low (below 3%) compared to the total number of events of each case. Furthermore, we achieve reasonable runtimes for the Randstad network with the most complex scenario (case 3) taking roughly an hour and 18 minutes. We also observe that the runtime is not necessarily proportional to the number of additional headway constraints: The second case generates approximately 6% more extra headway activities than the first one, but the latter takes four times longer to solve.

Table 2 – *Numerical results. For each case, we solve to optimality and report the number of cancelled events, the delaying and advancing results (including the number of delayed/advanced events, the total delayed/advanced times (in minutes), the maximum, minimum, and average delayed/advanced times (in minutes), respectively), and the total runtimes (in seconds).*

Case	**Cancel**	**Delay**					**Advance**					**Runtime**
	# events	**# events**	**Total**	**Max.**	**Min.**	**Avg.**	**# events**	**Total**	**Max.**	**Min.**	**Avg.**	
1	0	106 (1.95%)	107.4	2.7	0.2	1.0	26 (0.48%)	2.6	0.1	0.1	0.1	2480.4
2	0	6 (0.11%)	4.8	0.8	0.8	0.8	0 (0.00%)	-	-	-	-	599.5
3	0	2 (0.03%)	2.8	1.4	1.4	1.4	2 (0.04%)	2.0	1.0	1.0	1.0	4665.6

The events are delayed (resp. advanced) at most 2.7 minutes (resp. 1.0 minutes), and the average shifts in time per event are reasonable with the largest one being 1.5 minutes. Therefore, we conclude that the model can provide solutions with good quality, in which the number of cancellations is minimised and the adjusted times are relatively small. Furthermore, we test a parameter setting where delaying and advancing get the same penalty of 1 per minure, resulting in a higher number of advanced events for all cases. This suggests that the solution structure depends on the penalty values, and practitioners can customise their desired weights for each event. For example, important or popular services can be assigned to higher penalty values such that the adjustment made on them is minimised.

For future research, we aim to apply our approach to the entire Dutch railway network. To improve the runtimes, techniques such as node aggregation can be considered to reduce the size of the extended EANs. Another direction is to investigate the integration of relevant problems, e.g., passenger transfers, rolling stock scheduling, or crew scheduling, into the TTAP. Alternatively, one may be interested in developing an algorithm to handle large-scale instances.

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