Transportation Research Part C 77 (2017) 134–160

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Integrating robust timetabling in line plan optimization for railway systems ☆

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ARTICLE INFO

Article history:
Received 20 April 2016
Received in revised form 16 January 2017
Accepted 19 January 2017

Keywords:
Railway line planning
Timetabling
Robustness
Mixed integer linear programming

ABSTRACT

We propose a heuristic algorithm to build a railway line plan from scratch that minimizes passenger travel time and operator cost and for which a feasible and robust timetable exists. A line planning module and a timetabling module work iteratively and interactively. The line planning module creates an initial line plan. The timetabling module evaluates the line plan and identifies a critical line based on minimum buffer times between train pairs. The line planning module proposes a new line plan in which the time length of the critical line is modified in order to provide more flexibility in the schedule. This flexibility is used during timetabling to improve the robustness of the railway system. The algorithm is validated on the DSB S-tog network of Copenhagen, which is a high frequency railway system, where overtakings are not allowed. This network has a rather simple structure, but is constrained by limited shunt capacity. While the operator and passenger cost remain close to those of the initially and (for these costs) optimally built line plan, the timetable corresponding to the finally developed robust line plan significantly improves the minimum buffer time, and thus the robustness, in eight out of ten studied cases.

1. Introduction

Railway line planning is the problem of constructing a set of lines in a railway network that meet some particular requirements. A line is often taken to be a route in a high-level infrastructure graph ignoring precise details of platforms, junctions, etc. In our case, a line is a route in the network together with a stopping pattern for the stations along that route, as a line may either stop at or bypass a station on its route (which saves time for bypassing passengers). We define a line plan as a set of such routes, each with a stopping pattern and frequency, which together must meet certain targets such as providing a minimal service at every station.

Timetabling is the problem of assigning precise utilization times for infrastructure resources to every train in the rail system. These times must ensure that trains can follow their routes in the network, stop at appropriate stations where necessary, and avoid any conflicts with other trains. A conflict rises where two trains want to use the same part of the infrastructure at the same time, for example at a switch, platform or turning track. According to Bešinović et al. (2016) a timetable is feasible if all trains are able to adhere to the schedule on their assigned routes, we cite: "if (i) the individual

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☆ This article belongs to the Virtual Special Issue on "Integr Rail Optimization".

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http://dx.doi.org/10.1016/j.trc.2017.01.015
0968-090X/

processes are realizable within their scheduled process times, and (ii) the scheduled train paths are conflict free, i.e., all trains can proceed undisturbed by other traffic." Since in this research the running times, dwell times and turn times of the trains are fixed in advance and thus always realizable, this research focuses on constructing a normative macroscopically feasible timetable. If timetabling is performed separately from line planning, the line plan specifies the lines and the number of hourly trains operating on each line but not the exact times for those trains and not the precise resources that a train on a line will utilize. Those timings and utilizations are decided as part of the timetabling.

Traditionally, a railway line plan is constructed before a timetable is made. However, an optimal line plan does not guarantee an optimal or even a feasible timetable (Kaspi and Raviv, 2013). An integrated approach can overcome this problem. Nevertheless, since line planning and timetabling are both separately already very complex problems for large railway networks (Michaelis and Schöbel, 2009; Goerigk et al., 2013), solving the resulting integrated problem is in most cases not computationally possible (Schöbel, 2015). We propose a heuristic algorithm that constructs a line plan for which a feasible timetable exists. We call a line plan *timetable-feasible* if there exists a normative macroscopically feasible timetable for that line plan. Moreover the algorithm improves the robustness of the line plan by making well chosen changes in the stopping patterns of the lines while the existence of a feasible timetable remains assured.

There are different interpretations of robustness in railway research. According to Dewilde et al. (2011), a railway planning is *passenger robust* if the total travel time in practice of all passengers is minimized in case of frequently occurring small delays. The focus of this definition is twofold, as both short and reliable travel times have to be provided by the planning. Passenger robustness is also what we want to strive for with our approach. However, this objective is not directly included, but implicitly considered by avoiding delay propagation. If delays are less likely to be propagated between trains, fewer passengers will be delayed which positively affects the total passenger travel time in practice.

We have developed an iterative approach to build a line plan and timetable from scratch while taking passenger robustness into consideration. We focus on the integration of both planning problems. A line plan, optimal for a weighted sum of passenger and operator cost, can be created and iteratively updated until a normative macroscopically feasible and passenger robust timetable can be computed while keeping the quality of the line plan high. The main contributions presented in this paper are:

- The integration of line planning, timetabling and passenger robustness.
- An approach that builds coordinated line plans and timetables *from scratch*.
- Two insights and proofs on timetable-infeasibility of line plans.
- The inclusion of limited shunt capacity of terminal stations in line plan and timetable optimization.
- Practical conclusions for the DSB S-tog network in Copenhagen based on experimental results.

The context of this research is a high frequency network. The network can be large but should have a simple structure and trains are forced to turn on their platform in their terminal stations due to a lack of shunting area.

The proposed integrated approach originates from insights on why some line plans do not allow feasible timetables and why some line plans allow more robust timetables. A first insight is that a line can be infeasible on its own, which we call *line infeasibility*. A second insight is that line combinations can be infeasible due to their frequencies. We call this *frequency combination infeasibility*. In Section 3 we explain these insights. Furthermore, we present a technique to develop a line plan that guarantees a feasible timetable. We introduce a timetabling model based on the Periodic Event Scheduling Problem (PESP), introduced by Serafini and Ukovich (1989), to create passenger robust timetables. We illustrate with a case study that a smart and targeted interaction of both techniques develops a line plan from scratch which guarantees a feasible and passenger robust timetable. Moreover, the integrated approach can also be used to improve the robustness of an existing line plan. The line planning and timetabling technique and the integrated approach are explained in Section 4.

Related work and some definitions are discussed initially in Section 2. The case study is described in more detail in Section 5. In Section 6 the results of the case study are presented and examined and the integrated approach is illustrated in an example. The paper is concluded and ideas for future research are suggested in Section 7.

2. State of the art

The planning of a railway system consists of several decisions on different planning horizons (Lusby et al., 2011). The construction of railway infrastructure and a line planning are long term decisions. A timetable, a routing plan, a rolling stock schedule and a crew schedule are made several months up to a couple of years in advance. Decisions on handling delays and obstructions in daily operation are made in real time. Each of these decisions affects the performance of the other decisions. Ideally, a model that optimizes all these decisions simultaneously is preferred. Each of the separate decision problems, however, is NP-hard for realistic networks (Schöbel, 2015). In practice these planning decisions are usually made one after the other, although the solution from a previous decision level problem does not even guarantee that a feasible solution exists for the next level problem (Schöbel, 2015). In the case that the output of the previous decision level leads to infeasibility at the next planning step, there are several possible approaches for looking for a feasible solution to both planning levels together. First, the outcome of the previous level can be replaced by a second best outcome in the hope that a feasible solution for the next level exists. Secondly, the outcome of the previous level can be specifically oriented towards making a