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Reduced railway traffic delays using a MILP approach to increase Robustness in Critical Points☆

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ABSTRACT

Maintaining high on-time performance and at the same time having high capacity utilization is a challenge for several railway traffic systems and especially those with heterogeneous traffic. With high capacity utilization the system is sensitive to disturbances and delays could easily propagate in the network. One way to handle this problem is to create more robust timetables; timetables that can absorb delays and prevent them from propagating. This paper presents an optimization approach to reduce the propagation of delays by introducing a more efficient margin time allocation in the timetable. A Mixed Integer Linear Programming (MILP) model is proposed, in which the existing margin time is re-allocated to increase the robustness of an existing timetable. The model re-allocates both runtime and headway margin time to increase the robustness at specific delay sensitive points in a timetable, a suitable approach for double-track lines with dense heterogeneous traffic. We illustrate the applicability of the approach in a real-world case, where an initial timetable is modified into new timetables with increased robustness. These new timetables are then evaluated and compared to the initial timetable. We evaluate how the re-allocation of margin time affects the timetable structure and the timetable's capability to handle disturbances by exposing it to some minor initial disturbances in the range of 5–10 min. The results show that it is possible to reduce the delays by re-allocating the existing margin time. For example, the total delay at end station decreases with 10% in our real-world example.

1. Introduction

Over the two last decades the railway traffic has increased with 23% around the world (number of passengers travelling with railway (UNECE, 2014)). This has resulted in high capacity utilization of the railway network, which combined with frequent disturbances have led to an insufficient on-time performance. Even for small everyday disturbances, the trains may have problems to recover from them and they could easily propagate in the network. This is particularly the case for

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heterogeneous train traffic systems. One way to handle the disturbances is to create a more robust timetable, i.e. a timetable in which trains are able to keep their originally planned train slots despite small disturbances and without causing unrecoverable delays to other trains. A robust timetable should also be able to recover from small delays and prevent the delays from propagating in the network. Due to heterogeneous traffic and interdependencies between the trains there are points in the timetable that are particularly sensitive to disturbances. If the robustness in these critical points could be improved, the whole timetable would gain in delay recovery capability.

This paper presents an analysis of the possibility to improve train traffic punctuality by increasing the timetable robustness. The aim is to find an efficient approach to increase timetable robustness merely by re-allocating already existing margin time in a timetable to increase the available margin time in the critical points. The considered planning stage for the approach is when an initial timetable has been created based on the operators' requests. We then want to fine-tune the timetable and make it more robust, before it is put into operation. This approach can be used to re-allocate the margin time by shifting some trains backwards or forwards in time to achieve a new feasible timetable with higher robustness. The proposed approach is suitable for non-periodic timetables with heterogeneous traffic.

In this paper we present a Mixed Integer Linear Programming (MILP) model where existing margin time is re-allocated. We illustrate the applicability of the approach for a real-world case where we modify an initial timetable and create new timetables with higher robustness. Results from an experimental evaluation of how the timetables are able to handle certain disturbances, are also presented.

2. Related work

In the literature, several ways to measure robustness are proposed and discussed. The measures can be either related to timetable characteristics (ex-ante measures) or based on traffic performance (ex-post measures). We here use the term 'measure' in the same meaning as 'metric'. We refer to Andersson et al. (2013) for a benchmark of several ex-ante measures. These measures are suitable for comparing different timetables with respect to their robustness, but not often practically used to improve the robustness.

Ex-post robustness measures are by far the more common of the two types of measures mentioned, both in research and practice. Typically, ex-post measures are based on punctuality, delays, number of violated connections, or number of trains being on-time to a station (possibly weighted by the number of passengers affected). For example, Büker and Seybold (2012) measure punctuality, mean delay and delay variance, Larsen et al. (2013) use secondary and total delays as performance indicators and Medeossi et al. (2011) measure the conflict probability. A frequently used measure is the average or total arrival delay at stations, for example Vromans et al. (2006), Kroon et al. (2008), Fischetti et al. (2009) and Khan and Zhou (2010) use there measures.

The robustness of a timetable can be evaluated by optimization-based frameworks, see e.g. Corman et al. (2014), by simulation methods, see Salido et al. (2012) and Goerigk et al. (2013), by analytical methods, see Goverde (2007) or by Monte Carlo simulation, see Takeuchi et al. (2007). However, these frameworks are only evaluations of a given timetable. They can give insights in what influences the robustness, but do not provide a new timetable with a higher robustness. To create a robust timetable other models are needed.

The area of constructing nominal (initial and feasible) and robust railway timetables has been studied in previous literature with a diversity of approaches, see for example Cacchiani and Toth (2012) for a survey of the main works. Several approaches for real-time railway re-scheduling are presented in Cacchiani et al. (2014), which is an area closely related to timetable construction.

The scheduling problem is often complex and it needs a structured method to find feasible, satisfying solutions, which makes optimization a suitable and common method. Harrod (2012) lists several optimization based models used for railway timetable construction and he also lists some models that take robustness into account. The survey by Caprara et al. (2011) lists several optimization problems in railway systems. They list robustness issues as one type of problem, which has gained increasing interest. The authors describe in a generic way a frequently used optimization procedure to create a robust timetable which we refer to as *stochastic optimization*. The first step in the stochastic optimization is to construct a nominal timetable, i.e. a feasible timetable with no consideration of delay recovery. The second step is to repeatedly expose the timetable to stochastic disturbance scenarios and optimize it with respect to these. Each scenario with a new disturbance results in a new optimization problem which means that the total optimization problem has a tendency to become very large. Vromans (2005), Kroon et al. (2008) and Fischetti et al. (2009) use this procedure with modifications. Also Khan and Zhou (2010) use a two-step stochastic optimisation model to allocate margin time in both the runtime and at stops.

Fischetti and Monaci (2009) use the term *light robustness* for their model in which they use a set of slack variables to measure the robustness of a solution. They describe this model as less time consuming than the standard stochastic models but say it is only applicable for specific problems.

Liebchen et al. (2009) present the concept of *recoverable robustness* which combines stochastic programming and robust optimization. The authors mean that a timetable is robust if it can be recovered by limited means in all likely scenarios and they try to minimize the repair cost (delay cost) for resolving disturbed scenarios.

Goerigk and Schöbel (2014) have extended the concept of stochastic two-stage optimization and present an approach called *recovery-to-optimality*. Here the recovery cost to the set of optimal solutions in each studied scenario is minimized to