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Improving recovery-to-optimality robustness through efficiency-balanced design of timetable structure

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ABSTRACT

To improve the service quality of the railway system (e.g., punctuality and travel times) and to enhance the robust timetabling methods further, this paper proposes an integrated two-stage approach to consider the recovery-to-optimality robustness into the optimized timetable design without predefined structure information (defined as flexible structure) such as initial departure times, overtaking stations, train order and buffer time. The first-stage timetabling model performs an iterative adjustment of all departure and arrival times to generate an optimal timetable with balanced efficiency and recovery-to-optimality robustness. The second-stage dispatching model evaluates the recovery-to-optimality robustness by simulating how each timetable generated from the first-stage could recover under a set of restricted scenarios of disturbances using the proposed dispatching algorithm. The concept of recovery-to-optimality is examined carefully for each timetable by selecting a set of optimally refined dispatching schedules with minimum recovery cost under each scenario of disturbance. The robustness evaluation process enables an updating of the timetable by using the generated dispatching schedules. Case studies were conducted in a railway corridor as a special case of a simple railway network to verify the effectiveness of the proposed approach. The results show that the proposed approach can effectively attain a good trade-off between the timetable efficiency and obtainable robustness for practical applications.

1. Introduction

Improving the service performances in terms of punctuality and travel time-based efficiency has been the most challenging task for railway operators. These performances of railway operations depend highly on the quality of the (planning) timetable, especially under different types of disturbance, such as major delays or any other unforeseen events that would occur in real-world operation. These delays occurring at an operational level can cause delay propagation to other trains, especially under tight track capacity constraints.

A promising alternative for the delay controlling problem is robust timetabling, which designs effective timetables with sufficient buffer times to absorb disturbances in the running and dwell times while fully utilizing the network capacity. The timetable structure information, such as train orders, stations for trains to perform the overtaking or meeting operations, directly influences the computation of the detailed timetable solution described by the specific departure and arrival times (with embedded buffer times). Designing a robust timetable with flexible structure (i.e., without predefined timetable structure information) reasonably improves

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the potential qualities of the solutions of the robust timetabling problem.

1.1. Literature review

A typical "nominal" Train Timetabling Problem (TTP) in the literature did not consider how to handle delays when designing a timetable. TTP consists of selecting the optimal time of departures and arrivals of trains from and at stations so that safety constraints and user requirements are satisfied. The paper by Cacchiani and Toth (2012) compared the distinction between different kinds of timetabling problems. In recent years, many studies have been devoted to periodic or non-periodic TTP using classical optimization algorithms or constructive heuristics (e.g., Brännlund et al., 1998; Caprara et al., 2002; Zhou and Zhong, 2005; Cacchiani et al., 2008; Masoud et al., 2014; Karoonsoontawong and Taptana, 2015; Murali et al., 2015). Additional conditions, such as incorporating rolling stock, passenger connections, train pathing and positions of sidings (railway tracks in stations available to perform meet and pass operations) into timetabling, were considered in studies by Kroon et al. (2012), Lee and Chen (2009), and Abid and Khan (2015). Furini and Kidd (2013) and Cacchiani et al. (2016) modelled the problem of timetabling at a node (railway station) of the railway network. Haahr and Kidd (2015) considered the Energy-Efficient Train Timetables Problem (EETTP), which required a careful synchronization of train departures. Castillo et al. (2016) proposed a time partitioning technique to divide the timetabling problem into several small problems. This method produced a notable reduction in the CPU computation time and led to safe (feasible) and practical solutions. The methods to improve the dynamic transportation service supply have been examined by Liu and Zhou (2016) and Mahmoudi and Zhou (2016). Harrod (2012) analysed the features of timetabling models (structure and capabilities) rather than their prior application.

The Rescheduling/Dispatching Problem describes how to apply a recovery strategy to the planning timetable and try to obtain a new feasible timetable rapidly while systematically considering the occurring delays and resulting train conflicts (e.g., Zhan et al., 2015; Krasemann, 2012; D'Ariano et al., 2008; Dündar and Şahin, 2013; Kecman et al., 2013; Quaglietta et al., 2015; Pouryousef et al., 2016). Many researchers also consider possibilities, such as the rerouting of trains on an N-track, the rescheduling of the rolling stock, and the rescheduling of the crew in the integrated decision process. Representative studies include papers by Veelenturf et al. (2016), Bešinović et al. (2015); Dollevoet et al. (2015), Corman et al. (2012), Meng and Zhou (2014), Cordeau et al. (1998). More details could be referred to Cacchiani et al. (2014) and Fang et al. (2015) for a comprehensive survey of models and algorithms for real-time railway rescheduling. Corman and Meng (2014) reviewed online approaches defined as adjusting plans to the actual ever-changing situation of traffic for other dynamic interrelated problems in railway traffic control.

In robust timetabling, the key question is when and for how long the buffer times have to be inserted to guarantee a good trade-off between the nominal quality (efficiency) and the delay resistance (robustness). There are various concepts of robust timetabling. Specifically, for the concept of strict robustness, the obtained timetable could ensure the feasibility under the realization of uncertain data for all admissible scenarios (e.g., Bertsimas and Sim, 2004; Goerigk and Schöbel, 2010). Since robustness is realized by the introduction of buffer times, it might be in conflict with the efficiency of the timetable. Therefore, over-strict robustness would have over-conservative impacts on the efficiency of normal railway scheduling. Light robustness could compensate for this disadvantage to a certain extent by adding slack to the constraints. A solution is considered as light robust if it satisfies these relaxed constraints (Fischetti and Monaci, 2009; Cacchiani et al., 2012).

For the concept of multi-stage robustness, the model usually contains a timetabling part for determining the timetable, and a simulation part for evaluating the robustness of the timetable under construction. Vansteenwegen and Oudheusden (2006) presented an efficient Linear Programming technique for creating robust timetables that performed well in improving passenger service, even in non-ideal circumstances. Bešinović et al. (2016) proposed an effective hierarchical framework, which includes a microscopic and macroscopic model, for timetable design. After proving the feasibility of the microscopic model, the robustness of the timetable was evaluated, and new operational running times were computed as necessary. This hierarchical framework for the optimal design of railway timetables gave a precise definition of the infrastructure slots and ensured that the effective design of dense timetables was operationally feasible (Bešinović et al., 2014). Goverde et al. (2016) extended the framework and presented a performance-based railway-timetabling framework. To compute a timetable explicitly driven by using a group of more comprehensive indicators, an integrated approach was used on three levels: microscopic, macroscopic, and a corridor fine-tuning level. To make the timetable maximally robust against stochastic disturbances, the stochastic optimization model was widely used (see, e.g. Kroon et al., 2008; Khan and Zhou, 2010; Meng and Zhou, 2011). The key point in using the stochastic optimization model is obtaining detailed probability distributions of the random variables, which may be subject to changes. However, some data may be completely unknown in advance, and the precision of the known data can be low.

Considering robustness and recoverability in a unified way has led to the recoverable robustness model that has been introduced by Liebchen et al. (2007). Finding the optimal timetable that can be made feasible, or recovered, with limited effort against a limited set of scenarios of primary delays fits well within the concept of recoverable robust timetabling (e.g., Cicerone et al., 2008; D'Angelo et al., 2011; Cicerone et al., 2009a, 2009b; Fischetti et al., 2009). It is similar to two-stage stochastic optimization, but the difference is that the recoverable robustness could avoid the necessity of obtaining detailed probability distributions of the random variables. Goerigk and Schöbel (2014) further considered the optimality of the recoverability when finding recoverable robust timetable based on the pre-defined train order.

There are also studies considering other factors in the robust timetabling problem. Dewilde et al. (2014) focused on how to improve the robustness around large railway stations. The method of routing trains to the platforms was optimized. Sels et al. (2016) constructed a robust timetable by minimizing the proposed objective function of total passenger travel time as expected in practice. The evaluation and indirect steering of all time-related decision variables in the system reduced passenger travel time and ensured the