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Integrating train scheduling and delay management in real-time railway traffic control

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ABSTRACT

Optimization models for railway traffic rescheduling tackle the problem of determining, in real-time, control actions to reducing the effect of disturbances in railway systems. In this field, mainly two research streams can be identified. On the one hand, train scheduling models are designed to include all conditions relevant to feasible and efficient operation of rail services, from the viewpoint of operations managers. On the other hand, delay management models focus on the impact of rescheduling decisions on the quality of service perceived by the passengers. Models in the first stream are mainly microscopic, while models in the second stream are mainly macroscopic.

This paper aims at merging these two streams of research by developing microscopic passenger-centric models, solution algorithms and lower bounds. Several fast heuristic methods are proposed, based on alternative decompositions of the model. A lower bound is proposed, consisting of the resolution of a set of min-cost flow problems with activation constraints. Computational experiments, based on multiple test cases of the real-world Dutch railway network, show that good quality solutions and lower bounds can be found within a limited computation time.

1. Introduction

In recent years, many European railway companies are experiencing increasing difficulties in meeting the ever increasing transport demand while ensuring good quality of service (QoS) to the passengers, under condition of the limited space and funds to build new infrastructure in bottleneck areas. These facts have stimulated the interest of practitioners and theoreticians to new and more effective approaches to railway traffic rescheduling aiming at the reduction of delays of trains and passengers.

The literature on this subject has experienced significant developments in the last years, see, e.g., Caprara et al. (2006), Cacchiani and Toth (2012), Cacchiani et al. (2014), Binder et al. (2014) and Fang et al. (2015). Train rescheduling is the activity of updating a current plan of operation (i.e., a schedule) in response to unplanned disturbances, carried out by updating running and passing times of trains, orders of trains on shared resources, transfer connections between trains. Train rescheduling is a necessary measure to limit delay propagation to other trains and occurs, e.g., whenever the current plan of operations is not feasible anymore. Rescheduling is more frequent when the timetable is less resilient to disturbances, which is the case, e.g., when the train traffic is close to the capacity saturation for some segments of the network.

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The existing optimization models for supporting train rescheduling can be classified according to different criteria. Concerning the detail of the railway infrastructure and railway operations, optimization models can be classified into microscopic and macroscopic representations. The former one aims at including in the model all the relevant details of the railway infrastructure and operations; the latter one restricts the description to the higher level features of the rail network. A different classification identifies operations-centric models, which focus on the minimization of railway operations objectives, such as train delays or punctuality; and passenger-centric models, which focus on the maximization of the QoS perceived by the passengers.

The recent trend in the railway traffic rescheduling literature is to incorporate an increasing level of detail and realism in the models while keeping the computation time of solution algorithms compatible with real-time applications, or by taking into account the impact of rescheduling decisions on the QoS perceived by the passengers. The two main streams of research fall in two categories: The *train scheduling* (TS) stream combines a microscopic representation with an operations-centric view, while the *delay management* (DM) stream combines a macroscopic representation with a passenger-centric view. This paper introduces and discusses a new stream of research, based on a microscopic passenger-centric model, to solve what is here called the *microscopic delay management* (MDM) problem. An earlier attempt in this stream of research (Dollevoet et al., 2014) is limited to check the local microscopic feasibility of a macroscopic DM solution.

With respect to the existing literature, we move a step forward toward the explicit consideration of passenger flows in the microscopic TS model. A new comprehensive and detailed mathematical model is introduced for the MDM problem, incorporating both the traffic regulations at a microscopic level and the passenger rerouting options in the constraints. Our objective is the minimization of passenger travel time.

Several algorithms for the MDM problem are proposed for the computation of the upper and lower bounds to the optimum. Algorithms for the upper bound computation are based on the decomposition of the MDM model, and on the iterated solution of the decomposed models. We show that good quality lower bounds can be quickly computed by solving a set of suitable min-cost flow problems with activation constraints. Overall, upper and lower bounds of good quality are quickly computed for real-world test cases.

The paper is organized as follows. Section 2 reviews the relevant literature on railway traffic rescheduling, focusing on TS, DM and the few approaches facing the combined MDM problem. Section 3 introduces the relevant definitions and notations, later used in Section 4 to describe the mathematical model of the MDM problem. Section 5 presents the considered lower bounds, while Section 6 illustrates the algorithms to compute upper bounds. Section 7 reports on the computational experiments on the test cases of the Dutch rail network, which demonstrate the potential of the proposed approaches. Some conclusions and directions for future research are reported in Section 8. Two numerical examples are reported in the appendices of the paper.

2. Literature review

This section discusses the literature on railway traffic rescheduling with specific consideration to the TS models, the DM models and the few existing approaches for MDM. The first stream of models focuses on the operations, and follows the typical performance indicators of railway traffic controllers. The second stream focuses on passenger-centric approaches with a simplified view of the railway infrastructure. In the third stream we review some recent approaches aiming to combine TS and DM models.

2.1. Train scheduling

The complexity of the TS problem stems from the limited overtaking capacity of railway lines and from the constraints of the safety system, caused by the signal status and speed restrictions. The competition of trains for the available capacity can be modeled only when a sufficient level of detail is considered. One of the most effective approaches to tackle such complexity is based on the blocking time theory (see, e.g., Hansen and Pachl, 2014) and on the alternative graph formulation of the blocking job shop scheduling model with no-swap constraints (Mascis and Pacciarelli, 2002). This problem has been shown to be NP-hard even in the feasibility case (Mascis and Pacciarelli, 2002). Advanced scheduling approaches based on the alternative graph model are able to quickly solve real-life instances in which train arrival times, orders and routes, are considered variable (see e.g. D'Ariano et al., 2007, 2008; Mannino and Mascis, 2009; Corman et al., 2010). Remarkable improvements with respect to the current practice and/or to the basic dispatching rules adopted in most practical applications are reported in these papers. Other approaches to TS based on Mixed Integer Linear Programs (MILPs) are reported, e.g., in Törnquist Krasemann (2011), Lamorgese and Mannino (2015), Meng and Zhou (2014) and Pellegrini et al. (2014). The goal of all these approaches is to find a *train schedule*, i.e., a departure/passing time for each train at each relevant point of the railway network, compatible with the real time position of each train and such that a suitable function of the train delays (e.g., maximum delays, total delays, etc.) is minimized. Such a goal can be achieved by all approaches in practical size networks and within a computation time compatible with real-time operations.

One weakness of all these models is the limited view of passenger needs and expectations, which are taken into account only indirectly, e.g., by penalizing train delays. Among the works trying to enlarge the scope of these approaches, Corman et al. (2011) propose an iterated lexicographic optimization of train delays, given a division of trains into classes. The delay