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A multi-criteria decision support methodology for real-time train scheduling

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ABSTRACT

This work addresses the real-time optimization of train scheduling decisions at a complex railway network during congested traffic situations. The problem of effectively managing train operations is particularly challenging, since it is necessary to incorporate the safety regulations into the optimization model and to consider key performance indicators. This paper deals with the development of a multi-criteria decision support methodology to help dispatchers in taking more informed decisions when dealing with real-time disturbances. Optimal train scheduling solutions are computed with high level precision in the modeling of the safety regulations and with consideration of state-of-the-art performance indicators. Mixed-integer linear programming formulations are proposed and solved via a commercial solver. For each problem instance, an iterative method is proposed to establish an efficient-inefficient classification of the best solutions provided by the formulations via a well-established non-parametric benchmarking technique: data envelopment analysis. Based on this classification, inefficient formulations are improved by the generation of additional linear constraints. Computational experiments are performed for practical-size instances from a Dutch railway network with mixed traffic and several disturbances. The method converges after a limited number of iterations, and returns a set of efficient solutions and the relative formulations.

1. Introduction

A key problem in real-time railway traffic management is to efficiently reschedule trains during operations (Cacchiani et al. (2014)). In this context, a *resource* is a set of rail elements that can host at most one train at a time (e.g., a block section); a *potential conflict* is a simultaneous request of a resource; a *consecutive delay* is a train delay generated by the resolution of potential conflicts. In presence of initial delays, the real-time train scheduling problem requires to detect potential conflicts between two or more trains in each resource and to globally solve them by taking into account the propagation of consecutive delays (D'Ariano, 2009, Kecman et al. (2013), Corman et al., 2014b). Due to the limited time available to take real-time decisions, train dispatchers usually have a limited view on the effects of conflict resolution methods and are not able to compare

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alternative solutions in terms of various performance indicators. In practice, the dispatching measures are often sub-optimal, and leave room for improvement. Moreover, there is no clear agreement in literature on the objective functions to be used as many should be considered, due to different stakeholders and operational aspects.

This paper deals with the development of a multi-criteria decision support methodology to help dispatchers in taking more informed decisions when dealing with real-time disturbance management. Optimal train scheduling solutions are computed with high level precision in the modeling of the safety regulations and with consideration of state-of-the-art performance indicators to be optimized in a given computation time period. To achieve this aim, the following scientific issues have to be addressed:

- Microscopic optimization models for the real-time train scheduling problem have to be utilized, each one taking into account multiple performance indicators, either in the objective function or in the problem constraints;
- The models are to be automatically created and solved in a short computation time, and to be assessed in terms of the various performance indicators;
- A quantitative technique is needed to automatically compare the best solutions computed for the different models, to select efficient solutions and to give suggestions for improving inefficient ones;
- A comprehensive computational analysis is required in order to provide a pool of good quality solutions.

The first issue is addressed by the implementation of *Mixed-Integer Linear Programming* (MILP) formulations based on the *alternative graph model* of the real-time train scheduling problem (D'Ariano et al., 2007, 2014). Since there is no generally recognized indicator, the investigation of suitable objectives to optimize is very important. We study a selection of the most used objectives in the related literature, including the minimization of the maximum (initial plus consecutive) delay (Mazzarello and Ottaviani, 2007), the maximum consecutive delay (D'Ariano et al., 2007A, Pellegrini et al., 2014), the maximum consecutive delay with consideration of train priorities (Corman et al., 2011A), the cumulative consecutive delays (Pellegrini et al., 2014), the weighted sum of deviations from the arrival/departure scheduled times (Caimi et al., 2012), the sum of all completion times (Dessouky et al., 2006), the sum of delays (Meng and Zhou, 2011, 2014), a weighted sum of delays (Higgins et al., 1996) with penalties when exceeding a threshold (Törnquist and Persson, 2007), the travel time of trains as a surrogate of energy consumption (Corman et al., 2009a).

All the objectives studied in this paper are *operational-centric* since they focus on the minimization of railway operations objectives with a train point of view, whereas other approaches are *passenger-centric* since they focus on the maximization of the quality of service perceived by the passengers (the latter approaches are investigated, e.g., in Tomii et al. (2005), Takeuchi et al. (2006), Caprara et al. (2006), Kanai et al. (2011), Sato et al. (2013), Binder et al. (2014), Cacchiani et al. (2014), Dollevoet et al. (2014)). However, the methodology proposed in this paper remains valid even if different types of objectives are proposed.

The second issue is organized in the construction of the MILP formulations via the alternative graph model, the resolution of each formulation via a MILP solver, the investigation of the resulting solutions via a post-processing analysis. The latter method assesses the quality of each solution in terms of the various performance indicators.

The third issue is addressed via a useful benchmarking technique, named *Data Envelopment Analysis* (DEA), for assessing the relative efficiency of the different solutions (Charnes et al., 1978). It uses linear programming (LP) to determine the relative efficiencies of a set of homogeneous (comparable) units. This is a non-parametric technique, used for performance measurement and benchmarking the model solutions computed by the MILP solver (viewed as units). The analysis is based on the determination of the technical efficiency frontier as the frontier (envelope) representing the best performance and is made up of the units (formulations) in the data set which are most efficient in transforming their inputs (computational resources) into outputs (optimization results). The interested reader is referred to Charnes et al. (1994) and Cooper et al. (2007) regarding DEA fundamentals.

In DEA analysis, the performance of a formulation on a particular problem instance is calculated by comparing it to the efficiency frontier directly determined from the data. An efficiency score is thus computed for each solution based on its distance from the efficient frontier determined by the envelope of data of all solutions. This analysis is based on the BCC DEA model (Banker et al., 1984) which assumes variable returns to scale input/output relationships, and produces, for each unit, an efficiency score and additional information.

For each inefficient unit, improvement targets are individuated using the concept of composite unit. The attributes of a composite unit (which is a hypothetical efficient unit) are determined by the projection of an inefficient unit to the efficiency frontier. The attributes are formed as a combination of specific efficient units, in the proportions indicated by the results of DEA analysis. Based on an analysis of the MILP solver solutions computed for each formulation, we first classify the solutions into efficient and inefficient in terms of the given set of performance indicators. Then, for all the inefficient solutions, we propose an iterative method in order to improve their performance. This method, in a first step, generates additional constraints and then calls for the MILP solver in order to solve the modified formulations. In a second step, a further DEA analysis is devoted to establish a new efficiency ranking. The iterative method ends after a stopping criteria. The efficient solutions obtained for the modified formulations and the values for each performance indicator are given to the dispatchers for the final selection of the train schedule to be implemented.