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A variable neighbourhood search for fast train scheduling and routing during disturbed railway traffic situations

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A R T I C L E I N F O

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A B S T R A C T

This paper focuses on the development of metaheuristic algorithms for the real-time traffic management problem of scheduling and routing trains in complex and busy railway networks. This key optimization problem can be formulated as a mixed integer linear program. However, since the problem is strongly NP-hard, heuristic algorithms are typically adopted in practice to compute good quality solutions in a short computation time. This paper presents a number of algorithmic improvements implemented in the AGLIBRARY optimization solver in order to improve the possibility of finding good quality solutions quickly. The optimization solver manages trains at the microscopic level of block sections and at a precision of seconds. The solver outcome is a detailed conflict-free train schedule, being able to avoid deadlock situations and to minimize train delays. The proposed algorithmic framework starts from a good initial solution for the train scheduling problem with fixed routes, obtained via a truncated branch-and-bound algorithm. Variable neighbourhood search or tabu search algorithms are then applied to improve the solution by re-routing some trains. The neighbourhood of a solution is characterized by the set of candidate trains to be re-routed and the available routes. Computational experiments are performed on railway networks from different countries and various sources of disturbance. The new algorithms often outperform a state-of-the-art tabu search algorithm and a commercial solver in terms of reduced computation times and/or train delays.

1. Introduction

In the last years, European railway companies are experiencing increasing difficulties to face the ever increasing transport demand while ensuring good quality of service to passengers, also due to the limited space and funds to build new infrastructure in bottleneck areas. These facts stimulated the interest for new effective Operations Research (OR) solutions for real-time train scheduling. This problem is faced by dispatchers, which have to modify orders, passing times and routes of trains (on-line train dispatching problem) in order to counter delays and keep traffic smooth.

In the train scheduling literature, there is a well-known difference between the level of sophistication of the theoretical results and algorithms and that of the methods that are employed in practice. While the theory typically address simplified problems, achieving optimal or near-optimal performance, the practice must face all the complexity of real-time operations, often with little attention to the performance level. This difference is especially evident for real-time scheduling, and train scheduling is not an exception. As a result, the poorly performing scheduling methods that are used in practice has a direct impact on the quality of service offered to the passengers, and the negative effects of disruptions on the regularity of railway traffic may last for hours after the end of the disruption (Kecman et al. [32]). However, there are recently many signals that the scheduling gap could be drastically reduced in the next few years. On the theoretical side, recent approaches to train scheduling tend to incorporate an increasing level of detail and realism in the models while keeping the computation time of the algorithms at an acceptable level. On the practical side, the railway industry is interested in assessing the suitability of these methods to the practical needs of real-time railway traffic management.

The design and implementation of advanced mathematical models is a prerequisite to the development of innovative decision support systems for solving the on-line train dispatching problem. This paper is concerned with the modelling of the conflict detection and resolution (CDR) problem for railway networks. The CDR

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problem is the real-time problem of computing a conflict-free and deadlock-free schedule compatible with the actual status of the network and such that the circulating trains arrive and depart with the smallest possible delay. To solve the CDR problem, a number of algorithmic improvements are implemented in the AGLIBRARY solver, a set of OR-based models and algorithms for complex practical scheduling problems developed at Roma Tre University. This solver is the main solution engine of the ROMA dispatching support system [22], used for instance in the EU project ON-TIME [20]. The solver is based on the alternative graph model introduced by Mascis and Pacciarelli [38] and on the following framework: a good initial solution for the scheduling problem with fixed routes is computed by the (truncated) branch-and-bound algorithm in [25]. Metaheuristics are then applied to improve the solution by re-routing some trains. This action corresponds to the concept of a move, from a metaheuristics perspective. In [13], a tabu search algorithm has been applied to solve practical-size railway instances for a Dutch test case in the Netherlands.

Previous research left open a number of relevant algorithmic issues. The first issue concerns the extent at which different search strategies and alternative solution methods might outperform the tabu search algorithm. A second issue is to quantify the algorithmic improvements, looking at a reduction of the computation time and at an improvement of solution quality. Both these issues motivate the development of the new metaheuristics proposed in this paper. The paper contributions are next outlined:

- We present routing neighbourhoods that differ from each other for the set of candidate trains to be re-routed in each move and for the available routing alternatives.
- We alternate the search for promising moves via systematic changes of a combination of neighbourhood structures, similarly to Moreno Pérez et al. [41], and present strategies for searching within these neighbourhoods based on variable neighbourhood search schemes [30].
- We use fast train scheduling heuristics for the evaluation of each neighbour.
- We apply the proposed algorithms to the management of complex CDR problems, characterized by busy traffic, multiple delayed trains and temporarily disrupted railway resources. The new metaheuristics are compared with a state-of-the-art tabu search algorithm [13] and with a commercial solver. Significantly better results are obtained in terms of a reduced time to compute the best-known (sometimes proven optimal) solutions, and for some CDR instances also in terms of an improved solution quality.
- We evaluate the algorithms over various real-world test cases, which feature different railway network characteristics and traffic flows.

Section 2 gives an overview of the literature related to the real-time railway traffic management. Section 3 formally defines the CDR problem and Section 4 presents mathematical formulations for this problem. Section 5 describes the algorithms of AGLIBRARY and the new metaheuristics proposed in this paper. Section 6 reports on the performance of the algorithms on various practical case studies from Italy, the Netherlands and UK. Section 7 summarizes the main paper findings and outlines future research directions. An appendix illustrates the neighbourhoods investigated in this work with a numerical example.

2. Literature review

The study of real-time train scheduling and routing problems received increasing attention in the literature in the last years. Early approaches (starting from the pioneering work of [50]) tend to solve very simplified problems that ignore the constraints of railway signalling, and that are only applicable for specific traffic situations or network configurations (e.g. a single line or a single junction), see the literature reviews in the following papers: Ahuja et al. [1]; Cacchiani et al. [5]; Cordeau et al. [10]; Fang et al. [29]; Hansen and Pachl [31]; Lusby et al. [36]; Meng and Zhou [40]; Pellegrini and Rodriguez [44]; Pellegrini et al. [43]; Törnquist and Persson [51]. Among the reasons for this gap between early theoretical works and practical needs are the inherent complexity of the real-time process and the strict time limits for taking and implementing decisions, which leave small margins to a computerized Decision Support System (DSS).

Effective DSSs must be able to provide the dispatcher with a conflict-free disposition schedule, which assigns a travel path and a start time to each train movement inside the considered time horizon and, additionally, minimizes the delays (and possibly the main broken connections) that could occur in the network. The main pre-requisite of a good DSS is the real-time ability to deal with actual traffic conditions and safety rules for practical networks. In other words, the solution provided by a DSS must be feasible in practice, since the human dispatcher may have not enough time to check and eventually adjust the schedule suggested by the DSS. A recognized approach to represent the feasibility of a railway schedule is provided by the blocking time theory, acknowledged as standard capacity estimation method by UIC in 2004 (Hansen and Pachl [31]), which represents a safe sequence of train movements in the railway network with the so-called blocking time stairways.

With the blocking time theory approach, the schedule of a train is individually feasible if a blocking time stairway is provided for it, starting from its current position and leaving each station (or each other relevant point in the network) not before the departure time prescribed by the timetable. A set of individually feasible blocking time stairways (one for each train) is globally feasible if no two blocking time stairways overlap. The timetable prescribes the set of trains that are expected to travel in the network within a certain time window, the stops for each train and a pair of (arrival, departure) times for each train and each stop. At other relevant points (e.g. at the exit from the network or specific relevant points between two consecutive stations) can be defined minimum and/or maximum pass through times.

Many models and algorithms for train re-scheduling have already been proposed in the literature, but only a few of them with successful application in practice. So far, the most successful attempt in the literature to incorporate the blocking time theory in an optimization model is based on the alternative graph model introduced by Mascis and Pacciarelli [38]. This model is a generalization of the disjunctive graph for job shop scheduling, in which each operation denotes the traversal of a resource of the network by a job (train). Effective applications to real-time train scheduling are described in D'Ariano et al. [25], Mannino and Mascis [37], Mazzarello and Ottaviani [39]. However, other promising approaches have been provided in the literature, either based on mathematical formulations (Cadarso and Marín [3]; Caimi et al. [7]; Lamorgese and Mannino [34]; Pellegrini et al. [43]; Rodriguez [46]; Şahin [47]; Törnquist and Persson [51]; Wegele et al. [54]) or on algorithmic approaches (Almodovar et al. [2]; Cai and Goh [6]; Cheng [8]; Chiu et al. [9]; Liu and Kozan [35]; Törnquist Krasemann [52]; Wegele and Schnieder [53]). Another important aspect when dealing with rail operations is the passenger behaviour (Cadarso et al. [4]; Corman et al. [19]; Dollevoet et al. [28]; Kroon et al. [33]), even if this latter aspect is not considered explicitly in this paper.

The alternative graph model allows to directly model the individual and global train schedule feasibility concepts expressed

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