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Lower and upper bound algorithms for the real-time train scheduling and routing problem in a railway network

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Abstract: This paper focuses on the development of new algorithms for the real-time train scheduling and routing problem in a complex and busy railway network. Since this is a strongly NP-hard problem and practical size instances are complex, simple heuristics are typically adopted in practice to compute feasible but low quality schedules in a short computation time. In order to compute good quality solutions, we consider a mixed-integer linear programming formulation of the problem and solve it with a commercial solver. However, the resolution of this formulation by a commercial solver often takes a too long computation time. Therefore, a new methodology based on the relaxation of some train routing constraints in the formulation is proposed for the quick computation of a good quality lower bound. The lower bound solution is then transformed via a constructive metaheuristic into a feasible schedule, representing a good quality upper bound to the problem. Computational experiments are performed on several disturbed traffic situations for two practical case studies from the Dutch and British railways. The results show that the new lower and upper bounds are computed in a few seconds and are often of similar quality to the ones computed by the commercial solver in hours of computation.

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1. INTRODUCTION

This work addresses the *Real-Time Train Scheduling and Routing Problem* (RTTSRP), i.e., the problem of computing in real time a conflict-free schedule for a set of trains circulating in a network within a time window $W = [t, t+\delta]$, given the position of the trains at time t and the status of the network in W. The objective function is the minimization of train delays. A schedule is conflict-free if it satisfies the railway traffic regulations, which prescribe a minimum separation between consecutive trains on a shared resource in order to ensure the safety of train movements and to avoid deadlock situations in the network.

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 (23)) 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, e.g., the literature reviews in the following papers: Ahuja et al. (1); Cacchiani et al. (2); Cordeau et al. (3); Corman and Meng (8) Fang et al. (14); Hansen and Pachl (15); Lusby et al. (17); Meng and Zhou (19); Pellegrini and Rodriguez (21); Pellegrini et al. (20); Törnquist and Persson (24). 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).

The *alternative graph* of Mascis and Pacciarelli (18) is among the few models in the literature that incorporate, within an optimization framework, the microscopic level of detail that is necessary to ensure the fulfillment of traffic regulations. This model generalizes the job shop scheduling model in order to deal with additional constraints. Each operation denotes the traversal of a resource (block/track section or station platform) by a job (train route).

A big-M Mixed Linear Integer Programming (MILP) formulation of the RTTSRP can be obtained from the alternative graph model by introducing a binary variable for each train ordering decision (i.e. an *alternative pair*) and a binary variable for each routing decision (13). The resulting problem is strongly NP-hard (18).

This paper reports on recent improvements implemented in the state-of-the-art optimization solver AGLIBRARY (9). The solver includes a branch and bound algorithm for scheduling trains with fixed routes (10) and a tabu search metaheuristic for re-routing trains (5).

Previous research left open two relevant issues. The first issue is how to certify the quality of the RTTSRP solutions in a short computation time by means of effective lower

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bounds. This issue is made difficult due to the poor quality of the lower bounds computed by MILP solvers, that are usually based on a linear relaxation of the big-M MILP formulation of the RTTSRP.

The second issue concerns with the computation of effective upper bounds through the development of new solution methods. Both these issues motivate this paper, whose contribution consists of the following algorithms.

A first algorithm is proposed for the computation of a lower bound for the RTTSRP. This is obtained by the construction of a particular alternative graph for a relaxed RTTSRP in which each train route is composed by two types of components: (i) *real operations* that are in common with all alternative routes of the associated train; (ii) *fictitious operations* that represent the shortest path between two real operations that can be linked by different routing alternatives for the associated train. For the latter type of component, no train ordering decision is modeled, disregarding the potential conflicts between trains. The resulting alternative graph is then solved to optimality by the branch and bound algorithm in (10).

A second algorithm is a constructive metaheuristic proposed in order to optimize the selection of default routes. This metaheuristic starts from the optimal solution obtained for the alternative graph of the relaxed RTTSRP problem and iteratively replaces the fictitious operations of each train with a particular routing alternative. The selection of the routing alternative is based on the evaluation of the insertion of various train routes via the construction of the corresponding alternative graph and the computation of train scheduling solutions via fast heuristics.

Computational experiments are performed on practical-size instances from the Dutch and British railways. The new algorithms often compute good quality lower and upper bounds to the optimal RTTSRP solutions in a shorter computation time compared to a commercial MILP solver.

2. PROBLEM DESCRIPTION

The RTTSRP must consider the following issues. The railway network is made by track sections and platform stops at stations. A train is not allowed to depart from a platform stop before its scheduled departure time and is considered late if arriving at the platform later than its scheduled arrival time. At a platform stop, the scheduled stopping time of each train is called *dwell time*.

Signals, interlocking and Automatic Train Protection (ATP) systems control the train traffic by imposing safety regulations between trains, setting up train routes and enforcing speed restrictions on running trains. Fixed block ATP systems ensure safety through the concept of block section, a part of the infrastructure that is exclusively assigned to at most one train at a time. Train movements can be modeled by a set of characteristic times, as follows. The *running time* of a train on a block section starts when its head (the first axle) enters the block section and ends when the train reaches the end of the block section.

Safety regulations impose a minimum separation between consecutive trains traveling on the same block section, which translates into a minimum *headway time* between the start of the running times of two consecutive trains on the same block section. This time depends on the length of the block section, as well as on other factors like the speed and length of the trains and includes the time between the entrance of the train head in a block section and the exit of its tail (the last axle) from the previous one, plus additional time margins to release the occupied block section and to take into account the sighting distance.

Disturbances affect train traffic flows in a railway network. We can distinguish between light traffic *perturbations* from neighbouring dispatching areas and heavy traffic *disruptions*. The former are light disturbances caused by a set of delayed trains in a dispatching area, while the latter are much stronger disturbances of the scheduled times and routes (e.g. due to some block sections being unavailable for a certain amount of time). Other kinds of disturbances include extensions to dwell times due to passengers boarding, connection constraints between trains, or technical problems; and running time prolongation because of headway conflicts between trains or technical failures.

Initial delays propagate between trains when solving potential conflicting routes. Namely, a *potential conflict* between two or more trains arises if the trains request the same resource within a time interval smaller than the minimum headway time between them. The solution of the potential conflict is to fix the order of trains over the resource; in that case, some of the approaching trains might be forced to decelerate and thus experiencing a consecutive delay. Those delays may propagate to other trains causing a domino effect of increasing traffic disturbances (16). In this paper, the objective function is the minimization of the maximum consecutive delay: the largest positive deviation from the scheduled times at relevant locations.

3. PROBLEM FORMULATION

This section describes our formulation of the RTTSRP. The RTTSRP can be divided into two sub-problems: (i) the selection of a route for each train, and (ii) the train scheduling decisions once the routes have been fixed. We first provide a brief description of the alternative graph model for sub-problem (ii), more information can be found e.g. in Corman et al. (4; 6; 7) and in D'Ariano et al. (10; 11; 12). We then present a big-M MILP formulation for the overall scheduling and routing problem.

3.1 Alternative graph model

The alternative graph (AG) model for sub-problem (ii) of the RTTSRP is a triple $G = (N, F, A)$ where $N = \{0, 1, ..., n-1, n\}$ is a set of nodes, F is a set of *fixed* directed arcs, and A a set of pairs of *alternative* directed arcs.

Each node, except the start 0 and end n nodes, is associated with the start of an operation krj, where k indicates the train, r the route chosen and j the resource it traverses. The start time t_{krj} of operation krj is the entrance time of train k with route r in resource j.

The fixed arcs are used to model running, dwell, connection, arrival, departure, and pass through times of trains. Let the resources p and j be two consecutive resources processed by train k with route r, the fixed arc $(krp, krj) \in$

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