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A Lagrangian heuristic framework for a real-life integrated planning problem of railway transportation resources

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A B S T R A C T

Train path (infrastructure), rolling stock and crew scheduling are three critical planning decisions in railway transportation. These resources are usually planned separately in a sequential process that typically starts from planning (1) train paths and goes further on to (2) rolling stock and (3) train drivers. Such a sequential approach helps to handle the complexity of the planning process and simplify the underlying mathematical models. However, it generates solutions with higher costs because the decisions taken at one step can drastically reduce the set of feasible solutions in the following steps. In this paper, we propose a Lagrangian heuristic framework to solve an integrated problem which globally and simultaneously considers the planning of two railway resources: Rolling stock units and train drivers. Based on a mixed integer linear programming formulation, this approach has two important characteristics in an industrial context: (i) It can tackle real-life integrated planning problems and (ii) the Lagrangian dual is solved by calling two proprietary software modules available at SNCF. Various relaxation schemes are analyzed. Moreover, coupling constraints are rewritten to improve the heuristic effectiveness. Numerical experiments on real-life instances illustrate the effectiveness of the Lagrangian heuristic, and the impact of various parameters is analyzed. Compared to a sequential approach, it leads to cost reductions and generates good solutions in a reasonable CPU time.

1. Introduction and industrial context

Train path (defined as the part of the infrastructure required to operate a train between two points of a railway network during a given time period), rolling stock and crew scheduling are three critical planning decisions in railway transportation. These resources are usually planned separately in a sequential process that typically starts from train paths and goes further on to rolling stock and train drivers:

1. Optimized planning of railway timetables (see for example Cacchiani and Toth, 2012). The commercial offer is considered by elaborating a space–time graph where each train corresponds to a path. This graph supports the booking of train paths in the railway infrastructure. Constructing an optimal railway timetable requires to consider the major constraints of the railway system, but often not the detailed constraints on rolling stock units and train drivers.

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2. Optimized planning of rolling stock (see for example in Alfieri et al. (2006), Fioole et al. (2006), Rouillon et al. (2006), Vaidyanathan et al. (2008)). This stage consists of planning the rolling stock to cover the train paths defined in Step 1. This is done based on the available number of rolling stock units of each type, and aims at satisfying all technical and functional constraints.
3. Optimized planning of train drivers (see for example Abbink et al., 2011; Hanafi and Kozan, 2014; Jütte and Thonemann, 2012; Shen et al., 2013). The first step of this stage consists of defining a set of working days (shifts) for the train drivers to cover the requirements of the plan for the rolling stock, while respecting all legal constraints. The second step aims at combining these working days in a consistent roster for each driver.

Optimization tools are sometimes used at some point in each of these steps. In particular, SNCF has already developed optimization tools for Steps 2 and 3. Such a sequential approach helps to handle the complexity of the planning process and simplify the underlying mathematical models. However, it generates solutions with higher cost because the decisions taken at one step can drastically reduce the set of feasible solutions in the following steps.

In this context, studying an integrated planning approach is relevant to increase the quality of the production process of railway transportation plans. Several decision-making problems can be identified when considering integrated planning of railway transportation resources (see for example Benhizia et al., 2011). In this paper, we focus on the case of fixed timetables where only rolling stock units and train drivers are planned in an integrated way.

Furthermore, and as mentioned in Benhizia et al. (2011), integrated planning approaches were already studied in the airline industry (Lohatepanont and Barnhart, 2004; Mercier and Soumis, 2007; Papadakos, 2009), and in public transportation (mainly bus scheduling, where crew costs may dominate vehicle costs) (Freling et al., 2003; Huisman et al., 2005; Huisman and Wagelmans, 2006; Mesquita et al., 2011, 2013; Mesquita and Paias, 2008; Rodrigues et al., 2006); and cost reductions ranging from 5% to 10% are reported. The authors in Freling et al. (2003), Huisman et al. (2005), and Huisman and Wagelmans (2006) are actually also using Lagrangian relaxation, but in a very different way than us. They use Lagrangian relaxation within a column generation approach (to solve the master problem and to build feasible solutions from the generated columns) to solve directly an integrated model, whereas we use Lagrangian relaxation to decompose the problem by relaxing coupling constraints (to avoid solving directly the integrated model) and to solve it with a Lagrangian heuristic.

Multiple journal papers have been devoted to rolling stock and train driver scheduling in the railway literature. Recent research on railway crew scheduling includes (Abbink et al., 2005, 2011). The first paper presents the practical impact of Operations Research to design crew schedules at the NS (Netherlands Railways). In cooperation with the same Dutch railway operator, the second paper proposes and validates an approach that combines Lagrangian heuristics, column generation and fixing techniques to solve very large crew scheduling problems. Jütte and Thonemann (2012) propose an effective column generation based decomposition algorithm based on a divide-and-price strategy to optimize on overlapping regions in parallel. The algorithm is validated on large-scale problem instances of a freight railway system. Recently, in Hanafi and Kozan (2014), after presenting a mathematical model for railway crew scheduling to minimize the number of crew shifts, the authors propose a constructive heuristic to generate initial solutions which is hybridized with a simulated annealing metaheuristic. Rolling stock planning problems have recently been studied in Fioole et al. (2006) and Alfieri et al. (2006). In particular, the second paper focuses on optimizing the numbers of train units of different types based on an integer multicommodity flow model. The robustness of rolling stock plans for passenger trains is investigated in Nielsen et al. (2012) and more recently in Kroon et al. (2014). In these four papers, the proposed approaches are validated on industrial instances of NS (Netherlands Railways). However, to our knowledge, no journal paper deals with the integration of rolling stock and train drivers when optimizing the transportation plan.

In this paper, we first present a mixed integer linear programming model to globally and simultaneously consider the planning of two railway resources in passenger railways systems: Heterogeneous rolling stock units and heterogeneous train drivers. Our contributions in this model are the constraints that are necessary to couple the two planning problems. The key parameters linking the two types of railway resources are the qualifications of train drivers on rolling stock types. Other human resources are necessary in trains (e.g. inspectors), but the drivers are the most critical resources since they are the only ones that are required to be qualified to operate a rolling stock type. A Lagrangian heuristic framework is then proposed to solve the integrated problem. Four relaxation schemes are discussed, and the coupling constraints are also rewritten to accelerate the convergence of the Lagrangian relaxation. This approach has two important characteristics in an industrial context: (i) It can tackle real-life integrated planning problems and (ii) The Lagrangian dual is solved by calling two proprietary software modules available at SNCF. Actually, an important advantage of our Lagrangian heuristic framework is that it can be used with different solution approaches for each of the two planning subproblems.

In the remainder of this paper, we present in Section 2 a mixed integer linear programming model for our integrated planning problem of railway resources. The Lagrangian relaxation heuristic approach is sketched in Section 3 while Section 4 provides some industrial implementation details. We then discuss, in Section 5, computational experiments on real-life instances extracted from the transportation plan of a French region (Bretagne). Some conclusions are finally drawn in Section 6.