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Optimization of periodic crew schedules with application of column generation method ☆

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ABSTRACT

We present an alternative approach to the problem of periodic crew scheduling. We introduce the concept of frames which leads us to a modeling approach which suits well the current practice of the majority of European railway operators. It results in a model facilitating column generation techniques resulting in a Dantzig-Wolfe type decomposition, and thus suitable for a parallel implementation in a high-performance computing environment. We exploit the properties of network flow models to avoid several additional integer constraints. We compare two approaches to solve the problem. The first approach consists of solving the original problem by single model. The second approach is our step-by-step column generation. The comparison is based on our implementation which we describe in detail along with its application to certain benchmark instances. The benchmarks originate in real or close-to-realistic problems from railway systems in Slovakia and Hungary. The case studies demonstrate that our model is well-suited for real-life applications.

1. Introduction

In this paper, we focus on the crew management problem in the tactical planning horizon, on the crew scheduling problem (CSP) in particular. The main task is to assign appropriate crew to trains running on a network, while there are crew pools of given capacities available at certain depots (home terminals). The crew work plan should comply with a number of rules – legal (e.g. trade union rules) and technological (operation based rules; e.g. brake test after each coupling of locomotive and train set, and considering of necessary time in the schedule). The set of personnel typically includes locomotive drivers, and in case of passenger railway transportation, the conductors.

The CSP has a broad coverage in the literature. The related works can be divided into two groups, those addressing American cases, and those which address the problem under European conditions. A good overview of the relevant approach to American conditions is given by Patty (2015). Our results address European cases. We refer to the annotated bibliography in Ernst et al. (2004) and the work of Friesz and Bernstein (2016) for an extensive collection of relevant references. Mathematical models are prevalently applied for solving crew scheduling problems of the airline industry (Barnhart et al., 1998; Desrosiers et al., 1995; Hoffmann and Padberg, 1993; Rios and Ross, 2010; Sölveling and Clark, 2014). In the railway industry, the sizes of the crew scheduling instances can be orders of magnitude larger than in the airline industry, which ruled out the application of these models in the railway industry until recently Wedelin (1995). However, the development in hard- and software enabled the application of such models in the railway industry as well (Caprara et al., 1997; Crainic et al., 2009;

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Kohl, 2003; Kroon and Fischetti, 2000; Veelenturf et al., 2012; Shiftan and Wilson, 1999), and it is still a subject of current active research. Abbink et al. (2005), for instance, describe the successful application of a model and the corresponding solution techniques for scheduling more than 6500 drivers and conductors of the Dutch railway operator. We refer to Abbink et al. (2011), Abbink (2014), Hartog et al. (2009), Kwan (2011), Mesquita et al. (2011), Yaghini et al. (2015) for more case studies. Several interesting papers describing integrated optimization (integrated approach) were published (Borndörfer et al., 2017; Gürkan et al., 2016; Luan et al., 2017) in last years. We mention works of Veelenturf et al. (2017) and Yue et al. (2016) too, were scheduling related problems and relevant real-time disruption management application or application for high-speed passenger rail corridors are described. Problems related to periodic schedules are relevant in public bus transport too, albeit the details of the problems are different. Column generation is a prevalently used technique in this case, see e.g. Kliewer et al. (2011). As for periodic problems in bus transportation, Amberg et al. (2011), for instance, consider integrated vehicle and crew scheduling in this case, aiming at the production of rosters with similar days, and use column generation for solving their models.

In the literature, there are several definitions of the CSP. In our case the crew management problem is described as an act of forming a set of feasible crew duties which comprise all jobs situated on a given part of railway network in a determined time period. Vaidyanathan and Ahuja mention it as "duty period" in terminology of the CSP (Patty, 2015, p. 165). The objective of the problem is usually either to maximize the number of duty periods assigned to crew or to minimize the total cost of them. Vaidyanathan and Ahuja describe it this way - "crews need to have minimum rest between assignments" (Patty, 2015, p. 163). As the arc-based mathematical model of the problem has an enormous magnitude making it impossible to solve, we concentrate on techniques facilitating the decomposition of the original problem into a series of smaller ones.

The first idea followed in the present paper comes from the fact that the jobs served by a crew within the considered time period (e.g. one week or one month) often repeat with some frequency corresponding to a day-period. In this case, the day-period can be solved instead of the much larger original one and the solution of the day-period problem can be repeated to obtain solution of the original problem. This time-decomposition is easy to perform, when such a day-period location exists that no job exceeds the borders of the day-period. Thus the day-period is not necessarily bounded by midnight. We assume, for sake of concreteness, that it lasts 24 h, but we deal with the general case of the time-decomposition.

We employ, in addition, another "network" decomposition technique, which is based on the Wolfe's decomposition (Dantzig and Wolfe, 1960). This leads to the path-based formulation (Desaulniers et al., 2005) of the day-period model, where a column generation technique is applied to master the problem. We apply both decomposition techniques simultaneously in the present work in order to extend the family of tools for solving a large crew management problem.

The most important input data for the planning procedure is the timetable of the trains defining the train path to be served (information about the departure time, arrival time, on-duty time, tie-up time, departure location, and arrival location for every train). In many cases, the rolling stock circulation plan is also given, as it influences the number and qualification of the required crews. Based on this and the given technological requirements, it is possible to define the elementary jobs that the crews have to perform. These are mostly trips, during which the crews have to perform their given tasks, but there are usually additional tasks such as the start and end of a daily shift, the preparation of the train to the trip, etc., which also have to be considered. Each job is defined by a starting and ending point in time and in space, and possibly by a crew skill requirement. The other inputs are usually the locations of the depots, and the data of the available crews per depot. (In a consideration aiming at the establishment of a recruitment plan, these might be flexible.) The optimization goal is typically a cost minimization, but there might be additional considerations regarding quality figures of the resulting schedule.

The common approach to the problem is to divide it into sub-problems of hierarchical planning. In the first step a set of feasible shifts is generated. A shift is a sequence of jobs that a crew can perform during workday, possibly extending to the next day (overnight shift). (In cases when the trains are running several days at long distances, of course, a shift can be defined differently, for example in North America.) Feasibility is considered in terms of legal and technological rules (shift durations and home and away terminals are, for instance, planned in this phase). The activity of duty generation is also known as "job pairing". One of the issues in this phase is the enormous number of possible shifts. There might be several approaches to overcome this issue (see e.g. Koniorczyk et al., 2015). In the second phase, the set covering problem is solved. It means that from all possible shifts that could theoretically exist, only a set of them is chosen. The shifts that are in this set must cover all jobs. The set covering (or, possibly, partitioning) problem, which attracted a significant attention in the literature, as it is a large-scale problem of this kind with a practical relevance (Caprara et al., 1997, 2007). The selected shifts should be ordered into sequences to be feasible for a crew. There are additional requirements such as weekends and the required resting time between shifts which have to be taken into account in this phase. These may already be assigned to particular personnel. In case of periodic crew scheduling, however, the shifts are ordered into rosters which are then realized by multiple personnel, typically starting its time period (e.g. month) with a different day of the roster (first job is starting in his home terminal). In this case, there is a third phase, that of rostering, when the rosters are assigned to a particular crew. Periodic crew scheduling is especially crucial in passenger railway transportation: as the timetable itself is periodic, conductors are usually scheduled periodically by most of European operators.

We deal with the first two phases: shift generation and the selection of shifts to be realized. This is a mid-term planning process, the planning horizon typically ranges a timetable validity range, within which the train paths can be considered as fixed. Solving of the crew scheduling problem by means of mathematical programming faces large dimensionality of the models describing the associated large instances of the problem. Especially in the case when, the problem is described by one complete model, which covers all characteristics of the crew scheduling problem of a railway operator, the problem