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The periodicity and robustness in a single-track train scheduling problem

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ABSTRACT

The most important operating problem in any railway industry is to produce robust train timetables with minimum delays. The train scheduling problem is defined as an application of job shop scheduling which is considered to be one of the most interesting research topics. This paper deals with scheduling different types of trains in a single railway track. The authors have focused on the robust and periodic aspects of produced timetables. This paper is also concerned with some applicable constraints, such as the acceleration and deceleration times, station capacity and headway constraints. The periodic timetable for railways is modeled based on the periodic event scheduling problem (PESP). Furthermore, a fuzzy approach is used to reach a tradeoff among the total train delays, the robustness of schedules, and the time interval between departures of trains from the same origins. To solve large-scale problems, a meta-heuristic algorithm based on simulated annealing (SA) is utilized and validated using some numerical examples on a periodic robust train scheduling problem. Finally, a robustness measure is defined in order to assure the effectiveness of the proposed SA to find robust solutions.

1. Introduction

Rail transportation planning is made of several steps, like analyzing passenger's demand, line planning, train schedule planning, rolling stock planning, and crew management [10]. Train routings [27] are considered as the input data for train scheduling problem (TSP), while the output of TSP is used for the rolling stock assignment problem [11]. TSP is considered as the most challenging problems in railway planning that affects the interests of customers and the cost saving utilization of existed infrastructures. A train timetable defines the planned arrival and departure times of trains to/from stations. The classic objective function is to minimize the total delays of trains. The idea can also be extended when other kinds of objectives, such as the minimization of the deviation from the working hours of crews and the fuel consumptions, are also considered. There are many practical cases, in which a small alteration of the data can make the optimal solution virtually infeasible. The main purpose of this paper is to present a mathematical model to solve robust periodic train scheduling with the consideration of noise in the travelling times. In a tight timetable, a delay not only affects train timings, but also may result in delay propagations among other trains. To absorb the noises occur in practice, and specially to prevent the propagation of delays among the trains, the times between departures and arrivals of trains from/to stations, called buffer times, would raise. One more desirable characteristic of train timetables is to increase the time interval among departures of trains from the same origins. This avoids crowded stations to yield poor services. Therefore, it is looked at a tradeoff in train delays, robustness, and time intervals of origins departures.

The organization of paper is as follows. The literature is reviewed briefly in Section 2. In Section 3, fuzzy job shop scheduling is described. In Section 4, after a brief explanation of the PESP, the fuzzy periodic job shop scheduling problem is introduced to address the framework of the periodic robust train scheduling problem presented in Section 5. Section 6 describes a meta-heuristic algorithm based on simulated annealing (SA) to solve large-scale problems. In Section 7, a new robustness measurement method is proposed. Finally, some numerical examples as well as a case study from the Iranian railroad are presented at Section 8. The conclusion remarks are given at the end to summarize the contribution of this paper.

2. Literature review

The recent studies related to train scheduling problems can be categorized into three sections: (1) classic train scheduling problems, (2) real-time train scheduling problems, and (3) robust train

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scheduling problems. In the remaining part of this section, the related studies are briefly reviewed.

2.1. Classic train scheduling problems

Zhou and Zhong [35] studied high and medium-speed train scheduling problems in a double-track railway routes with bi-objectives that are to minimize the travelling times and train delays. A branch-and-bound (B&B) method is used to solve the presented model. Ghoseiri et al. [10] proposed a mathematical model for the train scheduling problem minimizing the fuel consumption and train delays. Their model is solved in two steps: finding the Pareto frontier and then using distance-based method. Caprara et al. [4] studied the double-track, uni-directional train scheduling problem, considering the station capacity and track maintenance times constraints. To that end, a time-index is defined for the related variables. The proposed solving method is based on the lagrangian relaxation of some of the constraints. Zhou and Zhong [34] proposed a mathematical model for a single-track, bi-directional train scheduling problem. They introduced a solving method based on the B&B method. In order to reduce the required time to solve the problem, some methods to define the lower and upper bounds are proposed. Sepehri and Pourseyed-Aghaee [23] considered the single-track scheduling problem, and introduced a modified B&B method including four cutting plains to reach optimum solutions in a shorter time. Cacchiani et al. [3] proposed some exact and heuristic algorithms for train scheduling problems in periodic and aperiodic cases, based on linear relaxation methods.

2.2. Real-time train scheduling problems

D'Ariano et al. [6] studied the real-time scheduling problem based on the job shop scheduling problem. The problem is modeled based on the alternative graph. The proposed method to solve the problem, is based on the branch and bound algorithm. Sahin [21] studied the train re-scheduling problem. The proposed solving method is based on heuristic algorithms that are to minimize train delays respecting the planned timetable. Adenso-Diaz et al. [1] studied the train rescheduling problem, in which an unwilling event affects the train movements. They proposed a heuristic algorithm and a decision support system to define necessary decisions whenever a disruption has happened. Walker et al. [32] studied the combined train and crew scheduling problem in a single railway condition. The objectives are to minimize total delays, and the deviation from crew working plans. They also studied the real-time scheduling when a disruption has occurred. A B&B method is proposed to solve the mathematical model. Mazzarello and Ottaviani [15] introduced a railway traffic management system. For this purpose, the system further to the all information related to the railway infrastructure (e.g., topography, maximum allowable speed, signals conditions) uses the necessary information about the dynamic position of trains in the railway network as the input data. They proposed an alternative graph formulation to solve the online conflicts whenever a disruption has occurred. Tornquist and Persson [29] studied the real-time scheduling problem. They considered single, double and multi tracks railway lines, and setup times, i.e., the time when two consecutive block sections are occupied by a single train. They proposed four methods to solve the given problem.

2.3. Robust train scheduling problems

Fischetti et al. [8] proposed four methods to find robust schedules for train movements. Their proposed methods are based on the mixed integer programming, stochastic programming, and robust optimization techniques. Their approach contains two steps: (1) finding an optimum timetable and (2) finding a robust schedule by the assumption of fixed train orders in passing the block sections. Babar Khan and Zhou [2] proposed a two-stage stochastic recourse model for the train scheduling problem, in a double-track scheduling environment. The stochastic parameters are shortest block section travelling times and origin departure times. In the first stage, the departure/arrival times from/to stations are computed. In the second stage, considering each of the scenarios, the deviation from the plan is computed. The objective is to minimize the total travel times and the expected value of deviations. A strong assumption in this paper is to schedule high-speed trains in the first priority disregarding the medium-speed trains and scheduling the medium-speed trains in the second priority. Fischetti and Monaci [7] proposed a heuristic method to formulate the uncertainty called light robustness. The proposed method is based on the combination of robust optimization and simplified two-stage stochastic programming approach. Kroon et al. [13] studied the robust train scheduling problem. To that end, they proposed a stochastic model to assign time supplements to block section travelling times, considering only one train. In the next step, they extended the model to improve an existing periodic train schedule. Further to the train scheduling problem, there have been some efforts conducted regarding robustness issues on delay management problems. For example, Vansteenwegen and Oudheusden [30], D'Angelo et al. [5] and Odijk et al. [19] proposed a new definition of timetable robustness. The idea is based on the fact that each timetable belongs to precisely one sequence, and each sequence partitions the set of timetables into timetable classes. They said that if a timetable class contains many different timetables, the timetables are called robust. Robust timetable classes have the property that slight perturbations to the input data can be dealt with by modifying the timetable within its class. They defined a new probability distribution that assigns higher probability to classes containing robust timetable classes. Shafia et al. [26] applied the idea of robust optimization approach to the train timetabling problem. Shafia et al. [25] used the same idea for the job shop scheduling problem..

Robustness and periodicity are two issues that are recently studied by a number of researchers. In this paper, the periodicity is achieved using the periodic event scheduling problem (PESP) firstly introduced by Serafini and Ukovich [24]. In this domain, there have been tremendous efforts to apply this formulation to train scheduling problems [14,20,31]. On the other hand, the main methods, which address the robustness issues, are based on the stochastic optimization and robust optimization approaches. The mentioned methods are computationally time-consuming to be solved. Therefore some simplifying assumptions are mostly used to achieve robust schedules. Moreover, these methods need some information about the disruptions, which rarely exist in the railway systems. A simple method to reach a robust timetable is to add some time intervals between each pair of events, i.e., arrivals or departures, known as *buffer times*. One can say that as the size of the buffer times increases, the timetable is more robust against disruptions; however, the objective function value (i.e., total travel times) worsens. In the current paper, in order to reach a robust schedule a new fuzzy method is used. For this reason, the amount of *buffer times*, are considered to be in fuzzy mood. Moreover the time intervals among departures of trains that should be departed from the same origins, called *origin departure times*, are supposed to be in the same mood. The problem is to find the timetables that not only minimize the total train delays but also maximize the buffer times and the time intervals among origin departure times. The authors use the job shop scheduling problem as the basis, and extend the model by introducing some applicable constraints. The mixture of periodicity, station capacity and acceleration, and deceleration constraints is another novelty of the paper. Moreover, a new robustness measure is defined to determine the capability of