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Multi-periodic train timetabling using a period-type-based Lagrangian relaxation decomposition

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ABSTRACT

To provide passengers with strict regularity of train operation, this research is devoted to modeling and solving the multi-periodic train timetabling problem to simultaneously optimize operation periods, arrival times, and departure times of all period types of trains on a double-track rail network. Based on the construction of a weighted directed graph, a multi-path searching model, namely, a 0-1 linear programming model, is built to minimize the total travel time of all period-types of trains subject to many operational constraints, including station parking capacity and train minimum load factors. After decomposing this model by introducing some Lagrangian multipliers to relax its complicated constraints, a solution algorithm, including a multi-path simultaneous searching sub-algorithm for each period-type of train, is designed to optimize both the feasible and dual solutions, which correspond to the upper and lower bounds, respectively. Finally, the performance, convergence, sensitivity, and practicability of our method are analyzed using many instances on both a small rail network and the high-speed railway between Beijing and Shanghai in China.

1. Introduction

A passenger-train timetable specifies the arrival, departure, and dwell times of all passenger trains at their traverse stations. It is not only the cornerstone of organizing station operation and the scheduling of motor-train units and crews for a rail enterprise, but also the means by which passengers choose trains to travel on a rail system. Thus, train timetabling has always been the key to organizing train operations, and rail enterprises attempt to solve the associated problems based on it. The achievement of an excellent train timetable with a high-efficiency approach obviously contributes to boosting the efficiency of train operation and reducing operating costs. Moreover, it can provide passengers with high-level service, which can attract more passengers, which benefits the rail enterprise. With increasing passenger service requirements and competition from air, expressway transport, etc., the pursuit of a service-oriented train timetable with high-level service is urgently needed to maintain and expand the market share of railways.

Train operation is generally organized in either a periodic or aperiodic way, with train timetables that we will respectively call periodic and aperiodic in this paper.

A periodic train timetable usually has a period of operation of just one length, such as one hour, and trains have the same operation order in all periods, with the same arrival times, departure times, and dwell times, as well as the same

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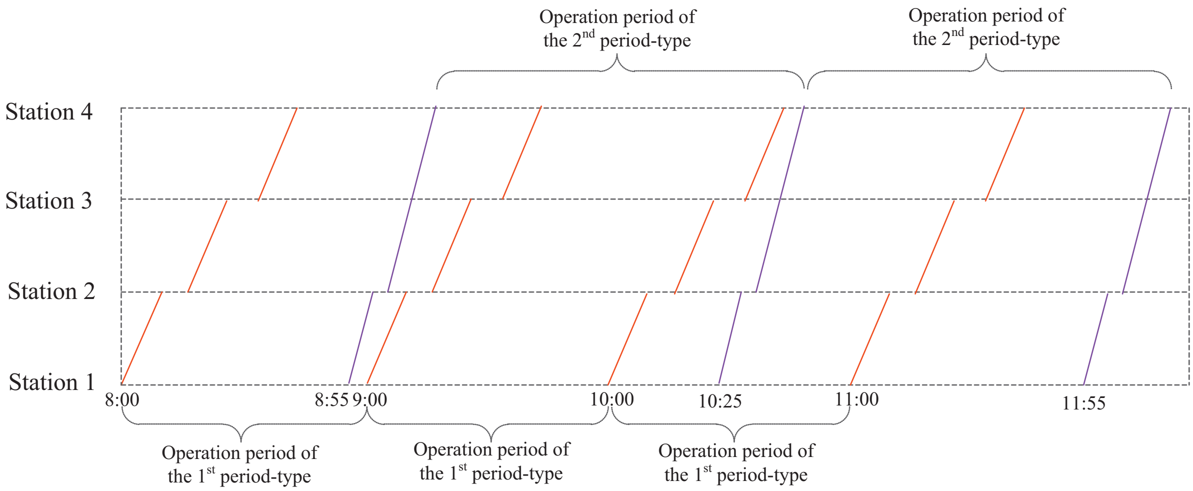

Fig. 1. A multi-periodic train timetable with two period-types of trains. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

overtaking and yielding patterns at stations. The regularity in train operations provides great convenience to passengers and simultaneously facilitates the organization of station operation for rail staffs. A periodic train timetable has been widely adopted in high-speed and metro systems in many countries such as France and Japan, and it shows good performance regarding passenger service levels and operational efficiency.

Aperiodic train timetables are also widely used in many countries, such as China. An aperiodic train timetable does not require trains to operate with the same rhythm in different periods. It allows trains to depart from stations at any time within a reasonable range, as long as they do not violate constraints imposed by the operation of other trains. This contributes to the matching of the time distribution of trains with that of passenger demand, which can better guarantee a certain passenger service level and efficiency of train operations.

A third type of timetable, a periodic train timetable with multiple operation periods, has been studied as well. For example, Odijk (1996) and Nachtigall (1996) pointed out that trains belonging to different families can have various operation periods, and Zhou and Yang (2016) focused on the train timetabling problem based on a multi-period combined operation. The periodic train timetable with multiple operation periods is called a multi-periodic train timetable, in which trains of the same period type have the same origin, terminal, traverse, stop stations, and operation speed, and they arrive and depart from stations with the same headway. To better explain this type of periodic train timetable, Fig. 1 shows a multi-periodic train timetable with two period-types of trains, displayed with red and blue lines, respectively, with trains of the first and second period-types operating with periods of 1 h and 1.5 h, respectively.

The multi-periodic train timetable has the following two main advantages over a periodic train timetable with only one operation period: (1) It can make the time distribution of trains better fit that of passenger demands through coordinating the period lengths, arrival times, and departure times of trains of all period-types. (2) Trains of each period-type have strict regularity of periodic operation. That is, they arrive at and depart from stations with a strict time interval, while trains in a common periodic train timetable no longer have a strict periodicity because of the cancellation of trains in off-peak periods. However, this type of periodic train timetable generally are available mainly for uncrowded rail corridors because it is very hard to find a feasible solution when scheduling lots of trains, especially also considering the overtaking operations.

Although some literature, such as Odijk (1996) and Zhou and Yang (2016), has referred to the concept of a multi-periodic train timetable, and moreover, Zhou et al. (2016) proposed a method for multi-periodic train timetabling with given period lengths, few studies have focused on the optimization of multi-periodic train timetables, especially the simultaneous optimization of the operation periods, arrival times, and departure times of all period-types of trains. However, it is crucial to simultaneously optimize them because it is difficult to determine a reasonable period for each period-type of train in advance, as it is tightly linked to train arrival and departure times.

Our research is devoted to modeling the multi-periodic train timetabling problem on a high-speed rail network consisting of double one-way tracks in each section, and designing a solution algorithm based on the period-type-based Lagrangian relaxation decomposition. One primary challenge is to simultaneously optimize the operation periods, arrival times, and departure times of all period-types of trains. We attempt to provide the following two main contributions to research work on the train timetabling problem.

(1) Formulate the multi-periodic train timetabling problem as a multi-path searching model of trains based on the construction of a weighted, directed graph. The proposed model not only aims to simultaneously optimize the arrival times, departure times, and operation periods of all period-types of trains, but also to provide an easy mechanism for period-type-based Lagrangian relaxation decompositions.