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Simultaneous passenger train routing and timetabling using an efficient train-based Lagrangian relaxation decomposition

Wenliang Zhou[a,*], Hualiang Teng[b]

[a] School of Traffic and Transportation Engineering, Central South University, Changsha 410075, China
[b] Howard R. Hughes College of Engineering, University of Nevada, Las Vegas, NV 89154, USA

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ABSTRACT

This paper focuses on the simultaneous passenger train routing and timetabling problem on the rail network consisting of both unidirectional and bidirectional tracks using an efficient train-based Lagrangian relaxation decomposition. We first build an integer linear programming model with many 0–1 binary and non-negative integer decision variables, after then reformulate it as a train path-choice model for providing an easier train-based Lagrangian relaxation decomposition mechanism based on the construction of space-time discretized network extending from node-cell-based rail network. Moreover, through reformulating safety usage interval restrictions with a smaller number of constraints in this reformulated model, the train-based decomposition needs fewer Lagrangian multipliers to relax these constraints. On the basis of this decomposition, a solving framework including a heuristic algorithm is proposed to simultaneously optimize both the dual and feasible solutions. A set of numerical experiments demonstrate the proposed Lagrangian relaxation decomposition approach has better performances in terms of minimizing both train travel time and computational times.

1. Introduction

Planning a high efficiency and safe train timetable plays a critical role in the operation and management in rail system, and it also becomes more difficult due to the expansion of rail network scale and the increase of train number. Train timetabling generally aims to describe how trains move in a detailed space-time area so as to further construct a timetable, with the objective of minimizing such as total travel time of all trains, which specifies 1) exact train paths through their passing stations, and 2) train arrival times and departure times at their passing stations, and is subject to many safety and operational constraints such as the safe interval between train departure times and minimum train dwell times at stations. Although most existing literature (e.g. Carey and Crawford (2007) and Castillo et al. (2011)) preferred to sequentially determine train routes and timetable for mainly reducing their solving complexities and difficulties, these two components are deeply interrelated and should be optimized together which is a clear trend towards the development of effective solution algorithms and CPU computing ability.

Rail train timetabling problem is an important issue and difficult to solve, and thus it has attracted considerable attention. Many studies related it have been done in the past few decades. Cacchiani and Toth (2012) presented an overview of the main works on nominal and robust train timetabling problems. The existing literature has adopted many efficient

* Corresponding authors.
E-mail addresses: zwl_0631@csu.edu.cn (W. Zhou), Hualiang.Teng@unlv.edu (H. Teng).

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methods such as branch and bound method, and Lagrangian relaxation approach for solving this problem. So far mathematical programming method is still one of the most popular approaches because of its higher computational efficiency and effectiveness. For single-track line train timetable problem, Szpigel (1973) formulated the train timetabling problem as a mixed-integer programming model with given routes and departure times of trains on a single track railway and designed a branch-and-bound algorithm to solve it. Carey (1994) detailed a mathematical programming model for train pathing and planning. Higgins et al. (1996) considered train priority in dealing with the conflict of meet and pass, for which a branch-and-bound method is applied. Focusing on passenger train timetabling problem, Ghoseiri et al. (2004) built a multi-objective optimization model and solved it by firstly using the ε-constraint method to obtain the Pareto frontier, after then adopting the distance-based method to seek a feasible solution. Zhou and Zhong (2007) proposed a generalized resource constrained formulation and a branch-and-bound solution procedure to obtain feasible train timetable with guaranteed optimality in a single-track railway network. For simultaneous train routing and timetabling problem, Caimi et al. (2011) developed an integer linear programming formulation and used the cutting plane method to solve it. Meng and Zhou (2011) incorporated different probabilistic scenarios in the rolling horizon decision process based on a stochastic programming with recourse framework for rescheduling trains after a major service disruption on a single-track rail line. Pellegrini et al. (2014) proposed a mixed-integer linear programming formulation for seeking the best train routing and scheduling in case of perturbation in the real-time railway traffic management. Castillo et al. (2015) proposed a linear programming program for train routing and timetabling by presenting alternate double-single track lines as an alternative to double-track lines. Yang et al (2016) built a multi-objective mixed integer linear programming model to collaboratively optimize train scheduling and train stop planning. Robenek et al. (2016) modeled the passenger centric train timetabling problem as a mixed integer linear programming problem.

However, in regard to the large-scale and real-world train timetabling problem, the performance of mathematical programming methods is not as satisfactory as them are applied in a relatively smaller one. It is difficult or impossible for them to explore alternative timetables. Alternatively, simulation and some heuristic approaches are widely applied to the large-scale and real-world train timetabling problems in recent years. This is because they can usually obtain a satisfactory train timetable instead of the optimal one within an acceptable computing time. Dorfman and Medanic (2004) proposed a local feedback-based travel advance strategy using a discrete event model to simulate train advances along lines of the large-scale railway and quickly handle perturbations in the schedule. Based on this effective train travel advance strategy, Li et al. (2008) further presented an improved train travel advance strategy relying on the global information of trains. Xu et al. (2014) combined this travel advance strategy with the genetic algorithm to find an optimal balanced train timetable with a least delay ratio as well as an optimal train velocity on the railway line. In terms of heuristic algorithms, Suteewong (2006) introduced a genetic algorithm to solve the train scheduling problem. Carey and Crawford (2007) developed an efficient heuristic algorithm to assist the task of finding and resolving conflicts in the draft of train schedules on the complex rail networks. Corman et al. (2010) alternated a fast heuristic and a truncated branch and bound algorithm in the tabu search scheme for train conflict detection and resolution when computing train schedules. Mu and Dessouky (2011) introduced two heuristics based on a simple insertion procedure and the genetic algorithm method respectively to solve the train timetabling problem considering flexible path of trains respectively. Boccia et al. (2013) described two heuristic approaches to solve the dispatching problem on multi-track territories based on a mixed integer linear programming formulation. Cacchiani et al. (2015) proposed an iterative heuristic algorithm for train timetabling problem in the context of a highly congested railway node consisting of a set of stations interconnected by tracks. Castillo et al. (2016) proposed a time partitioning technique of train timetabling by considering small time windows in which the timetables of a small number of running trains are optimized in sequence. Goverde et al. (2016) proposed a three-level solving framework for performance-based railway train scheduling. Samà et al. (2016) designed a variable neighborhood search algorithm for fast train scheduling and routing during disturbed rail traffic situations. Unfortunately, simulation and heuristic methods also have some limitations. For example, simulation approaches generally have low global optimization capacity as they mainly simulate train moving process with some given rules. Heuristic methods cannot always ensure solution qualities, and they even possibly trap in local optimum after limited iterations although they theoretically have a capability of global with enough iterations.

Another good idea for solving the large-scale and real-world train timetabling problem is to decompose the original complex train timetabling problem into multiple simple and tractable problems by either decomposing the larger rail network into multiple small ones or decomposing these interrelated trains into independent trains, after that, repeatedly coordinate the solving of multiple simple sub-problems to obtain the final solutions of original problem. This decomposition idea not only reduces the complexity and solving difficulty of the original train timetabling problem, but also can obtain a satisfactory train timetable with less computing time. Carey and Lockwood (1995) solved the train timetabling problem by dispatching trains one by one, which virtually is a simple train-based decomposition method. Brännlund et al. (1998) used a Lagrangian relaxation solution approach to separate the original train schedule problem into one train-based dynamic program by relaxing track capacity constraints and assigning usage prices for them. Caprara et al. (2002) formulated an integer linear programming model relaxed in a Lagrangian way to solve the train timetabling problem. Lee and Chen (2009) decomposed the complex train routing and timetabling problem into four parts: ordering trains on inter-station tracks, assigning trains to tracks, ordering trains on intra-station tracks, and finally solving train schedule in order to design a high efficient algorithm for it. Meng and Zhou (2014) decomposed the original complex rerouting and rescheduling problem into a sequence of single train optimization sub-problems by reformulating the infrastructure capacity using a vector of cumulative flow variables,