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Coordinating assignment and routing decisions in transit vehicle schedules: A variable-splitting Lagrangian decomposition approach for solution symmetry breaking

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ABSTRACT

This paper focuses on how to coordinate a critical set of assignment and routing decisions in a class of multiple-depot transit vehicle scheduling problems. The assignment decision aims to assign a set of transit vehicles from their current locations to trip tasks in a given timetable, where the routing decision needs to route different vehicles to perform the assigned tasks and return to the depot or designated layover locations. When applying the general purpose solvers and task-oriented Lagrangian relaxation framework for real world instances, a thorny issue is that different but indistinguishable vehicles from the same depot or similar locations could commit to the same set of tasks. This inherent solution symmetry property causes extremely difficult computational barriers for effectively eliminating identical solutions, and the lower bound solutions could contain many infeasible vehicle-to-task matches, leading to large optimality gaps. To systematically coordinate the assignment and routing decisions and further dynamically break symmetry during the solution search process, we adopt a variable-splitting approach to introduce task-specific and vehicle-distinguishable Lagrangian multipliers and then propose a sequential assignment process in order to enhance the solution quality for the augmented models with tight formulations. We conduct the numerical experiments to offer the managerial interpretation and examine solution quality of the proposed approach in a wider range of applications.

1. Introduction

The Transit Vehicle Scheduling Problem (TVSP) has received significant attention from the public transportation field (Saha, 1970; Löbel, 1998; Steinzen et al., 2010; Ibarra-Rojas et al., 2015), and its core model can be found in many applications in different areas of transportation science and logistics, such as urban rail transit, freight distribution, and civil aviation operations. In a typical transit planning and operating process, the timetabling stage (Cacchiani and Toth, 2012; Niu and Zhou, 2013; Niu et al., 2015a,b) first concentrates on providing a high level of service for passengers, while the subsequent transit vehicle scheduling stage (Gavish et al., 1978; Ceder and Stern, 1981; Daduna and Paixão, 1995) aims to reduce the overall operational vehicle cost to meet the timetabled trip tasks, while considering a fixed or variable fleet size.

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The traditional modeling framework for the transit vehicle scheduling problem is built on a connection-based network (Carraresi and Gallo, 1984), where trips and depots are represented by nodes, and possible connections between nodes are defined using arcs. By recognizing that the connection-based method could lead to an immense number of connection arcs for a medium or large-scale instance, a space-time based network representation has been commonly used (Hane et al., 1995; Kliewer et al., 2006; Steinzen et al., 2010). A few network reduction techniques (Kliewer et al., 2006; Li and Balakrishnan, 2016) have also been proposed to further reduce the network size.

In general, TVSP is a NP-hard problem due to its inherent combinatorial nature (Bertossi et al., 1987; Haghani and Banihashemi, 2002). The single-depot TVSP problem can be solved easily by using a specially developed network (Gartfinkel and Nemhauser, 1969). However, for the multiple-depot case with multiple indistinguishable vehicles, there exists a huge number of equivalent symmetric solutions, and one could obtain them by simply re-indexing vehicle IDs. The structurally inherent symmetry creates extremely difficult computational barriers for a branch and bound/cut based search process or a Lagrangian relaxation based decomposition method to effectively eliminate identical solutions. Interested readers are referred to two seminal papers by Sherali and Smith (2001) and Margot (2010) on the theoretical analysis of solution symmetry in various integer programming models and typical symmetry reduction methods in connection with the use of standard optimization solvers such as CPLEX.

In a more general case of TVSP, the Vehicle Scheduling Problem (VSP) has been well studied in both fields of transportation science and operations research (Ball et al., 1983; Desaulniers and Hickman, 2007; Pepin et al., 2009). Depending on their respective constructed networks, there are two common modeling approaches including arc-oriented and path-oriented. Usually, the arc-oriented approach leads to a multi-commodity flow formulation (Forbes et al., 1994; Löbel, 1998; Haghani et al., 2003; Lin and Kwan, 2016a), but it is difficult to directly solve the resulting integer programming models with thousands of trip tasks being scheduled/assigned especially when based on connection-based networks. The path-oriented modeling approach selects from an extensively large pool of routing variables that result in a set partitioning formulation (Ribeiro and Soumis, 1994; Dell'Amico et al., 1993). In order to avoid path enumeration, the column generation approach has been successfully applied (Desrosiers et al., 1992; Rousseau et al., 2004) to solve the restricted master problem and the pricing sub-problem. A number of researchers Huisman et al. (2005) and Steinzen et al. (2010) have further refined the column generation approach for the integrated vehicle and crew scheduling problem. Recently, Uçar et al. (2017) designed a novel column-and-row generation algorithm, where the pricing sub-problem can generate pairs of routes for recovery solutions, to solve the disruptions in the multi-depot vehicle scheduling problem.

When considering the complex space-time task structure of a transit vehicle scheduling problem, there are several major challenges in effectively applying the column generation approach for large-scale real-world instances. First, there are too many alternative space-time paths/columns to be considered when the adjusted pricing variables on space-time arcs are given. Second, it requires a very sophisticated branch and price mechanism to solve the set partition problems for large sets of space-time paths and tasks. Third, when homogeneous vehicles are scheduled from the same depot, the above-mentioned solution symmetry issue still exists and can cause a very slow "tailing off" effect in the branch-and-bound convergence process.

Considerable efforts have also been devoted to practice-oriented decomposing and relaxing algorithms for the multiple-depot vehicle scheduling problem (Solomon and Desrosiers, 1988). The task covering constraints (Geoffrion, 1974) or the flow conservative constraint (Lamatsch, 1992; Kokott and Lobel, 1996) can be relaxed within the commonly used Lagrangian relaxation framework. Again, the sub-problems from the arc-based decomposition must deal with the inherent symmetry issue: several homogeneous vehicles are apt to perform the same task competitively as the transportation cost and arc-based Lagrangian multipliers are exactly the same for each set of identical vehicles. The Lagrangian decomposition approach pioneered by Fisher et al. (1997) aims to dualize the vehicle routing problem into a semi-assignment problem and a series of shortest path problems so that the decomposed sub-problems can utilize vehicle-specific prices to better assign vehicles to different tasks. Since it is still difficult to handle possible task-covering competition and conflict in the lower bound solutions, they also applied a branch-and-bound based method to generate and improve feasible solutions.

To obtain high-quality solutions heuristically, Bodin et al. (1983) and Ropke and Pisinger (2006) examined the large neighborhood search approach and Taillard et al. (1997) proposed a tabu search heuristic for the vehicle scheduling problem with soft time windows, in which a neighborhood of the current solution is created through an exchange procedure that swaps sequences of consecutive customers between two routes. Koskosidis et al. (1992) presented optimization-based heuristics within a cluster-first and route-second framework. Fioole et al. (2006) addressed the railway rolling stock circulation problem which can handle underway combining and splitting of trains. Cacchiani et al. (2010) and Cacchiani et al. (2013) have carried out a series of excellent research on train unit assignment problems in a regional area, and presented a computationally efficient Lagrangian heuristic rule to solve the NP-hard problem. Cadarso and Marín (2011) and Cadarso and Marín (2014) proposed several approaches to obtain better and more robust circulations of the rolling stock train units, which aimed to solve the rolling stock assignment and the train routing problem with Benders decomposition heuristic. Lin and Kwan (2016b) and Lusby et al. (2017) focused on the branch-and-price approach for solving the network-level train unit scheduling problem, and real-world problem instances were tested with various branching rules and adaptive node selection methods. Recently, Mahmoudi and Zhou (2016) proposed a high-dimensional state-space-time network representation to embed difficult constraints on vehicle routing problems with pickup and delivery services. They also noticed a task-based Lagrangian relaxation would work well for real-world ride-sharing test cases with vehicles de-