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Column generation based heuristic framework for the multiple-depot vehicle type scheduling problem

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A B S T R A C T

The multiple-depot vehicle-type scheduling problem (MDVTSP) is an extension of the classic multiple-depot vehicle scheduling problem (MDVSP), where heterogeneous fleet is considered. Although several mathematical formulations and solution methods have been developed for the MDVSP, the MDVTSP is still relatively unexplored. Large instances of the MDVTSP (involving thousands of trips and several depots and vehicle types) are still difficult to solve in a reasonable time. We introduce a heuristic framework, combining time–space network, truncated column generation (TCG) and state space reduction, to solve large instances of the MDVTSP. Extensive testing was carried out using random generated instances, in which a peak demand distribution was defined based on real-world data from public transportation systems in Brazil. Furthermore, experiments were carried out with a real instance from a Brazilian city. The framework has been implemented in several algorithm variants, combining different developed pre-processing procedures, such as state space reduction and initial solutions for the TCG. Computational results show that all developed algorithms obtained very good performances both in quality and efficiency. The best solutions, considering simultaneously quality and efficiency, were obtained in the heuristics involving state space reduction.

1. Introduction

The multiple depot vehicle-type scheduling problem (MDVTSP) consists in finding the minimum cost assignment of a set of vehicles with different technical specifications from several depots to a set of trips previously defined. The MDVTSP can be seen as a generalization of the classic multiple-depot vehicle scheduling problem (MDVSP), where heterogeneous fleet is considered. The MDVTSP arises in a wide array of practical applications. Instances of MDVTSP occur in public transportation, maritime, rail, or air transportation. Because of our initial motivation, which arose from bus scheduling, in this paper special contextual reference is made to the MDVTSP in public transit systems, where a bad scheduling planning results in the increase of operational and fixed costs.

Although the literature describes several different approaches to solve the MDVSP (Pepin, Desaulniers, Hertz, & Huisman, 2009), the MDVTSP has not received the same attention in the literature than its counterpart (Ceder, 2011b). This is quite a surprise, since heterogeneous fleet is a common characteristic in transit networks of most large size cities around the world (Roman, 2012). Nevertheless, some solution methods were proposed in the literature to solve the MDVTSP, mainly based on heuristics (Hassold & Ceder, 2014). However, due to the huge size of the underlying vehicle scheduling network, they either solved limited size problems requiring very large amount of CPU time, or mischaracterized the problem, relaxing some of the related constraints. These limitations are restricting their application to real world transportation systems. The goal of this research is to address this gap in the literature.

This paper describes a heuristic framework based on column generation (CG) to solve very large instances of the MDVTSP with a good compromise between efficiency and quality of the solution. The whole heuristic framework consists of four sequential steps. In the first step, the vehicle underlying network is generated both as a time space network (TSN) and as a connection network. The second step is based on a state space reduction process intended to reduce the number of variables in the problem. In the third step, initial solutions for the next phase are generated, based on the developed reduction process of the second phase. Finally, the fourth step employs a CG approach to solve the original or the reduced problem to find near optimal solutions. Several algorithm variants were

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tested, combining these steps in a plug-and-play approach. The performance of these variants was assessed on randomly generated instances up to 3000 trips, 32 depots, and 8 vehicle types. Computational comparisons showed that some of the variants achieved very good results, requiring very competitive CPU time, to solve all tested instances. The developed algorithms constitute a viable alternative to solve efficiently the MDVTSP.

The contributions of this paper are as follows: (i) to introduce an efficient and effective state space reduction technique to decrease the MDVTSP complexity; (ii) to develop a customized truncated CG approach towards solving the MDVTSP with efficiency; (iii) to develop an integrated heuristic framework, combining several modeling and solution techniques, to accelerate the solution process; and (iv) to systematically analyze the performance of the developed algorithms that compose the heuristic framework.

The paper is organized as follows. Section 2 reviews the literature on the MDVTSP. Section 3 presents the developed mathematical formulation of the problem. The developed branch and price framework for solving the problem is presented in Section 4. In Section 4.1, a reduced state space procedure is proposed to further reduce computation times. Section 5 describes the computational experiments carried out to evaluate the performance of the algorithms. Finally, a summary of the results, and areas of future research are provided in Section 6.

2. Literature review

The literature on MDVTSP is still scarce, possibly reflecting the difficulty of solving the problem. In the MDVTSP, the number of possible vehicles routes, considering different depots and vehicle types, results in a combinatorial complexity for the problem. The MDVTSP was modeled and solved using similar methods than the ones developed for the MDVSP. Gintner, Kliewer, and Suhl (2005) and Kliewer, Mellouli, and Suhl (2006) developed heuristic methods to solve the MDVTSP, which main idea was initially to solve simplified models for each depot, and then search for commons chains in the solutions. If a common chain is included in a vehicle scheduling problem (SDVSP) solution, the authors classify this as a stable chain and assume that may occur in the global optimal solution. The stable chains were treated as the only trips, reducing the complexity of the MDVSP, in a direct application of standard optimization software. However, significant simplifications were made, mischaracterizing the problem as the classic MDVTSP, as follows: (i) one-depot-per-route requirement was relaxed, allowing a vehicle to start and finish its sequence of tasks in different depots; and (ii) each vehicle type was assigned to only one depot. With these simplifications, the authors solved instances up to 7068 trips and 5 depots, requiring 3 h of CPU time. van den Heuvel, van den Akker, and van Kooten Niekerk (2008) extended Gintner et al. (2005)'s formulation, explicitly adding the vehicle-type in the new formulation. In addition, passenger demand was also considered. However, to obtain a solution in a reasonable time, the authors considered only one depot and allowed more than one vehicle of the same type to perform a trip.

Some authors used alternative approaches to model and solve the MDVTSP. Laurent and Hao (2009) considered the heterogeneous fleet within the MDVSP, formulated as a graph coloring problem. An iterative tabu search method was employed to minimize the required number of vehicles. They tested the developed method in seven real instances with eight vehicle types. Good results in terms of solution quality and low computational times were obtained in the experiments. Oughalime, Ismail, Liong, and Ayob (2009) presented theoretical efforts to perform the integration of vehicle scheduling with heterogeneous fleet and crew scheduling. The authors proposed a sequential modeling that uses integer programming to solve the vehicle scheduling problem and a goal programming model for the crew scheduling. Although the research is constructed using a real example, no experiments were presented to validate the proposed model. Ramos, Reis, and Pedrosa (2011) modeled the MDVTSP as an asymmetric traveling salesman problem (ATSP). They proposed an ant colony heuristic method to solve the problem. However, as the ATSP is a well-known NP-complete problem, the developed approach presented some difficulties in finding good solutions in a reasonable time.

Ceder (2011b) used an innovative approach to solve the integration of the vehicle scheduling considering heterogeneous fleet, called Deficit-Function Theory (DFT). As defined in Ceder (2011b), the DFT is a heuristic method that uses the deficient number of vehicles in a particular terminal in a multi-terminal transport public system to solve the problem. The MDVTSP is formulated as a minimum cost network flow and solved using a heuristic procedure that allows flexible departure times of trips within a tolerance interval, following rules expressed in the DFT. The method was used in two small examples. Ceder (2011a) improved his heuristic framework, applying it to several sets of real data from the transit system of Auckland, New Zealand. Recently, Hassold and Ceder (2014) proposed a multi-objective model for the vehicle scheduling and timetabling generation integrated problem. The model allowed to stipulate the use of a particular vehicle type for a trip or to allow for a substitution either by a larger vehicle or a combination of smaller vehicles with the same or higher total capacity. Moreover, a variant in the method made it possible to construct sub-optimal timetables given a reduction in the vehicle scheduling cost. It was demonstrated that a substitution of vehicles is beneficial and can lead to significant cost reductions. However, the method can only be applied to individual bus lines, not considering interconnected lines or a set of lines, and therefore with limited applicability to the MDVTSP.

Although the literature has interesting and useful ideas towards the modeling and solution of the MDVTSP, most of the available algorithms are computationally intensive, requiring thousands of CPU seconds to solve real-world scheduling instances, involving thousands of trips, and dozens of vehicles and depots. Moreover, the quickest developed approaches relax some of the MDVTSP constraints and requisites, making it easier to find solutions. However, there is either limited notion of the quality of the obtained solutions, or their behavior in practical applications in real situations. As a consequence, it is unclear whether they can be directly applied to large instances of the classic MDVTSP problem.

3. Problem definition and formulation

The MDVTSP can be defined as follows. Given a set of vehicle types with significantly different attributes; a set of depots with their vehicle type capacity; a set of trips with fixed peak demand, and starting and ending times; given the travel times between all pair of locations, find a feasible minimum-cost scheduling in which (i) each vehicle performs a feasible sequence of trips, starting and ending in the same depot; (ii) the peak demand of each trip is always attended by a vehicle; and (iii) the capacity of each depot for each vehicle type is respected. Before defining a mathematical formulation for the problem, we first introduce the vehicle scheduling network.

3.1. Vehicle scheduling network

In order to represent the scheduling underlying network, a time–space network (TSN) structure was chosen rather than the more traditional connection network (Ribeiro & Soumis, 1994).