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The heterogeneous pickup and delivery problem with configurable vehicle capacity

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ABSTRACT

Various forms of the pickup and delivery problem (PDP) have been studied extensively over the past decades. This paper introduces a new version of the heterogeneous PDP in which the capacity of each vehicle can be modified by reconfiguring its interior to satisfy different types of customer demands. The work was motivated by a daily route planning problem arising at a senior activity center. A fleet of configurable vans is available each day to transport participants to and from the center as well as to secondary facilities for rehabilitative and medical treatment. The number of participants and support equipment that a van can accommodate depends on how it is configured.

The problem is modeled as a mixed-integer program much the same way as a PDP but with side constraints that add another level of complexity. To find solutions, we developed a two-phase heuristic that makes use of ideas from greedy randomized adaptive search procedures with multiple starts. In phase I, a set of good feasible solutions is constructed using a series of randomized procedures. A representative subset of those solutions is selected as candidates for improvement by solving a max diversity problem. In phase II, an adaptive large neighborhood search (ALNS) heuristic is used to find local optima by reconstructing portions of the feasible routes. Specialized removal and insertion heuristics were designed for this purpose. Also, a specialized route feasibility check with vehicle type reassignment is introduced to take full advantage of the heterogeneous nature of vehicles. The effectiveness of the proposed methodology is demonstrated by comparing the solutions it provided over a period of several weeks with those that were used in practice and derived manually. The analysis indicates that anywhere from 30% to 40% savings can be achieved with the multi-start ALNS heuristic.

1. Introduction

Pickup and delivery problems (PDPs) are at the center of a variety of applications in the transportation industry such as cargo delivery (Xu et al., 2003), home healthcare (Cordeau and Laporte, 2003), and driver work area design (Bard and Jarrah, 2009). In its basic form, the objective is to construct a set of minimum cost routes to satisfy transportation requests subject to flow balance, customer demand, vehicle capacity, and time window constraints. The problem can be viewed as a vehicle routing problem (VRP) with precedence constraints, in which each pickup has to be performed before the delivery for a given request.

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There are many variants of the PDP with regard to vehicle type, request type, and request handling. Demand can be serviced by either a homogeneous fleet or a heterogeneous fleet of vehicles with different capacities and operational costs. In the latter case, we have a heterogeneous PDP (HPDP) (Xu et al., 2003). When there is more than one request type, each may have different capacity requirements, and hence can only be serviced by the vehicles that possess the required capacity (Parragh, 2011). In the vast majority of cases, the capacity of a vehicle is fixed but in our case, we consider it to be adjustable or configurable. If a single request can be split into several smaller units and handled by multiple vehicles, then we have the case of a *split load* (Desaulniers, 2010). If a single request can be transferred from one vehicle another at some intermediary locations, then we have a *transshipment* option (Qu and Bard, 2012; Masson et al., 2012).

In general, the objective of the PDP is to minimize a weighted sum consisting of one or more of the following: the total number of vehicles used (Shang and Cuff, 1996; Nanry and Barnes, 2000; Li and Lim, 2001; Xu et al., 2003; Ropke and Pisinger, 2006); the total distance traveled by the vehicles (Shang and Cuff, 1996; Li and Lim, 2001; Xu et al., 2003; Ropke and Pisinger, 2006); the number of requests that are not satisfied (Shang and Cuff, 1996; Nanry and Barnes, 2000); the total time vehicles are operational (Li and Lim, 2001); vehicle waiting time (Shang and Cuff, 1996; Li and Lim, 2001; Xu et al., 2003) and passenger ride time as in this paper. Regardless of the specific form, the PDP is NP-hard in the strong sense since it is a generalization of the VRP.

In this paper, the focus is on the HPDP with multiple request types and configurable vehicle capacity. Our interest in this problem was triggered by a real application associated with daily route planning for a Program of All-Inclusive Care for the Elderly (PACE) organization. The situation they face can be described as follows. On a daily basis, a set of participants must be picked up at their place of residence within a preferred time window and transported to either an activity center for socializing, or to a secondary facility such as a diabetes clinic or doctor's office for medical treatment. Later that day they are transported back to their residence in their preferred time window. Most participants are ambulatory and simply need a seat in the van while others are wheelchair or walker bound and require more space. To accommodate a large mix of clients, PACE owns several different types of vehicles whose interiors can be readily modified to meet their transportation needs. For example, seats on a vehicle can be raised or removed to accommodate wheelchairs. Our objective is to first minimize the operational costs of providing service and then to minimize the number of vehicles used each day. A third objective is to minimize the average ride time of the participants. Since people rather than cargo are being transported, the application falls into the category of a static dial-a-ride problem.

The main contributions of this paper are threefold. First we present a new model for an unexamined variant of the PDP. Second, we develop a multi-start, adaptive large neighborhood search (MSALNS) algorithm to find solutions. The algorithm contains two phases. In phase I phase, a set of initial solutions is created with a greedy, randomized construction procedure. A promising subset of those solutions is then selected for further examination by solving a max diversity problem. In phase II, each candidate carried over from the first phase is improved with ALNS using reinsertion heuristics to intensify the search for local optima. The vehicle type assignments are made dynamically in both phases by solving transportation problems. The third contribution is the introduction of benchmark data sets that can be used by the research community to further study the HPDP and to design more efficient solution techniques.

In the next section, we discuss the related literature, which is followed by a description of the organization that motivated the research in Section 3. In Section 4, we give a formal definition of the problem and a mixed-integer programming formulation. Our solution procedure is described in Section 5, and computational test results are highlighted in Section 6 for data set provided by one of the PACE organizations. An analysis of the results shows that cost reductions ranging from 30% to 40% are possible. Conclusions are drawn in Section 7 where plans for future research are outlined.

2. Literature review

The VRP and its variants have been studied extensively in recent decades going back to the early work of Dantzig and Ramser (1959). A summary of solution approaches has been compiled by Toth and Vigo (2002) and Cordeau et al. (2007). The PDP, as a variant of the VRP with precedence constraints, has drawn similar attention over the past two decades with surveys presented by Savelsbergh and Sol (1995), Berbeglia et al. (2007) and Parragh et al. (2008). Many researchers have developed exact methods such as branch and cut, and branch and price, as well as state-of-the-art metaheuristics such as GRASP, Tabu search, simulated annealing, and large neighborhood search to solve these types of routing problems (e.g., see Bard et al., 2002; Desrochers et al., 1992; Kontoravdis and Bard, 1995; Nanry and Barnes, 2000; Osman, 1993; Ropke and Pisinger, 2006).

One well-studied PDP is the dial-a-ride problem (DARP) dealing with passenger transportation. A survey of models and algorithm can be found in Cordeau and Laporte (2003). Since our work is closely related to the static DARP, we highlight some of the more recent research in this area.

Parragh et al. (2010) proposed a variable neighborhood search (VNS) heuristic with three neighborhood definitions for the DARP. The heuristic was tested on 20 benchmark data sets from Cordeau and Laporte (2003), and new best solutions were found for 16 instances. Jain and Hentenryck (2011) introduced a constraint-based large neighborhood search which uses constraint programming to identify good insertions for customers. When compared to other start-of-art heuristics, they showed that their approach provided solutions at least as good as tabu search and variable neighborhood search.