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A hybrid algorithm for the vehicle routing problem with pickup and delivery and three-dimensional loading constraints

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A R T I C L E I N F O

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A B S T R A C T

In this paper, we extend the classical Pickup and Delivery Problem (PDP) to an integrated routing and three-dimensional loading problem, called PDP with three-dimensional loading constraints (3L-PDP). We are given a set of requests and a homogeneous fleet of vehicles. A set of routes of minimum total length has to be determined such that each request is transported from a loading site to the corresponding unloading site. In the 3L-PDP, each request is given as a set of 3D rectangular items (boxes) and the vehicle capacity is replaced by a 3D loading space. We investigate which constraints will ensure that no *re*loading effort will occur, i.e. that no box is moved after loading and before unloading. A spectrum of 3L-PDP variants is introduced with different characteristics in terms of reloading effort. We propose a hybrid algorithm for solving the 3L-PDP consisting of a routing and a packing procedure. The routing procedure modifies a well-known large neighborhood search for the 1D-PDP. A tree search heuristic is responsible for packing boxes. Computational experiments were carried out using 54 newly proposed 3L-PDP benchmark instances.

1. Introduction

Routing vehicles and loading them with goods represent two major challenges in transportation logistics. Routing and loading problems have to be tackled as integrated problems if companies are interested in optimizing both the routing of vehicles and the corresponding loading of goods. Gendreau, Iori, Laporte, and Martello (2006) first formulated and solved an integrated routing and loading problem, namely the capacitated vehicle routing problem (CVRP) with three-dimensional (3D) loading constraints (3L-CVRP). Contrasting to the classical CVRP, customer demands are represented as sets of parallel-epipeds (called boxes) and the scalar capacity of a vehicle is replaced by a 3D rectangular loading space. This essential modification allows for a more detailed modeling of mixed cargo transportation by vehicles. Several packing constraints, e.g. concerning stacking of goods, can only be considered if customer demands are viewed as sets of 3D items. To ensure that calculated routes can actually be implemented, a 3D modeling of cargo and loading spaces is in many situations indispensable (see Bortfeldt & Homberger, 2013). Thus it seems to be desirable to model and solve further types of vehicle routing problems (VRPs) as integrated routing and 3D loading problems (3L-VRP).

This task is tackled here for the classical Pickup and Delivery Problem (PDP). In the classical PDP, we are given a set of transportation requests that have to be served by a fleet of homogeneous vehicles with a uniform 1D capacity. Each request is characterized by a 1D demand that has to be transported from a *specific* loading site (pickup point) to a *specific* unloading site (delivery point). Since we have a single pickup point and single delivery point per request, the classical PDP belongs to the one-to-one VRPs with pickup and delivery. A set of routes, each starting and ending at the single depot, has to be constructed in such a way that (i) each request is served at only one route and its pickup point is visited before its delivery point; (ii) the capacity of a used vehicle is never exceeded by the set of loaded goods; (iii) the length of each route does not exceed a given limit; (iv) the number of routes does not exceed the given number of vehicles, and (v) the transportation cost, given by the total travel distance, is minimized.

To extend the classical PDP to an integrated routing and 3D loading problem, called hereafter PDP with three-dimensional loading constraints (3L-PDP), the demands are taken as sets of 3D rectangular items and the vehicles are equipped by a 3D rectangular loading space. As usual for the 3L-CVRP, we want to have a problem formulation that rules out any *re*loading effort. That is, the boxes should not be moved *after* loading and *before* unloading. In the 3L-CVRP this is guaranteed by the so-called Last-In-First-Out

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Table 1
Sample of heuristics for the classical PDP.

Reference	Type of heuristic
Nanry and Barnes (2000)	Reactive tabu search
Li and Lim (2001)	Tabu embedded simulated annealing
Lim, Lim, and Rodrigues (2002)	Squeeky wheel optimization
Pankratz (2005)	Grouping genetic algorithm
Lu and Dessouky (2006)	Construction heuristic
Bent and van Hentenryck (2006)	Hybrid algorithm: simulated annealing, large neighborhood search
Ropke and Pisinger (2006)	Adaptive large neighborhood search
Derigs and Döhmer (2008)	Indirect local search with greedy decoding
Nagata and Kobayashi (2010)	Guided ejection search

(LIFO) condition. It turns out that this constraint is not sufficient to eliminate any reloading effort for the 3L-PDP. Therefore, additional constraints are introduced for this purpose. This leads to a spectrum of 3L-PDP variants that are afterwards defined more formally.

A hybrid algorithm for solving the 3L-PDP is proposed that is composed of the modified large neighborhood search (LNS) algorithm by Ropke and Pisinger (2006) for the 1D-PDP and the tree search (TRS) algorithm for packing boxes by Bortfeldt (2012). The hybrid algorithm is tested by means of 54 newly introduced 3L-PDP benchmark instances with up to 100 requests.

The rest of the paper is organized as follows: Section 2 reviews the relevant literature. In Section 3 crucial features of the 3L-PDP are discussed and some variants of the 3L-PDP are formulated. Section 4 describes the hybrid algorithm, while in Section 5 numerical results of experiments are presented and analyzed. Conclusions are drawn and an outlook at further research is given in Section 6.

2. Related work

In our literature review, we will focus on recent work on the classical PDP with paired pickup and delivery points and on VRPs with loading constraints. In particular, we will consider recent papers on PDP with loading constraints. Moreover, we look for practical applications of 3L-PDP dealt with in this paper. We refer the reader to Toth and Vigo (2014) for a comprehensive survey on vehicle routing.

2.1. Solution methods for the classical PDP

In pickup and delivery problems, goods or passengers are transported between customers or institutions. Following the classification schema by Parragh, Doerner, and Hartl (2008) the classical PDP is characterized by paired pickup and delivery points, i.e. each pickup point is generally associated with a special delivery point and vice versa. Moreover, the PDP deals with the transportation of goods; hence, no special constraints and objectives are involved concerning the (in)convenience of passengers as in dial-a-ride problems. A further distinction can be made with regard to the number of available vehicles and we will consider only the multi vehicle case, while the single vehicle case, representing an immediate extension of the Traveling Salesman Problem (TSP), is not considered here.

Mathematical models of the classical PDP or PDP with time windows (PDPTW) can be found, e.g. in Parragh et al. (2008) and in Toth and Vigo (2014). Most of the published solution methods are surveyed by Berbeglia, Cordeau, Gribkovskaia, and Laporte (2007) and Parragh et al. (2008). The PDP is NP-hard, as it generalizes the TSP. Therefore, mainly classical heuristics and metaheuristics were proposed for solving the PDP. A representative sample of recent heuristics is listed in Table 1. For further details of the algorithms, the reader is referred to the references; some comments can be found in Parragh et al. (2008) and in Toth and Vigo (2014). For an introduction in metaheuristic approaches we refer to Gendreau and Potvin (2010).

All solution methods listed in Table 1 are developed for the PDPTW, i.e. time windows are always considered. However, service times are only taken into account by Li and Lim (2001), Nanri and Barnes (2000) and Ropke and Pisinger (2006). Almost all methods minimize the routing cost (total travel distance) and several methods do also minimize the number of routes. The multi depot case is only handled by Ropke and Pisinger (2006). Almost all methods of Table 1 assume that the vehicle fleet is homogeneous. The case of heterogeneous vehicles is dealt with by Xu, Chen, Rajagopal, and Arunapuram (2003) and Ropke and Pisinger (2006). Most of the solution methods listed in Table 1 are evaluated by means of the benchmark instances proposed by Li and Lim (2001). Outstanding results especially for larger instances were achieved through the neighborhood search methods by Bent and van Hentenryck (2006) and Ropke and Pisinger (2006), while the method of Li and Lim (2001) proved to be very successful for smaller instances.

A branch and cut algorithm for the PDPTW was proposed by Ropke, Cordeau, and Laporte (2007), while Ropke and Cordeau (2009) described a branch and cut and price algorithm. Baldacci, Bartolini, and Mingozzi (2011) recently presented an exact algorithm based on a set-partitioning-like integer formulation. These exact PDPTW algorithms are capable of solving PDPTW instances with up to 500 requests; nevertheless, the numerical results reveal that heuristic approaches remain indispensable for large PDP instances.

2.2. Vehicle routing problems with loading constraints

Iori and Martello (2010, 2013) and Pollaris, Braekers, Caris, Janssens, and Limbourg (2015) survey the state of the art in the field of integrated vehicle routing and loading problems. Generally, the literature is still limited and this applies in particular to VRPs with 3D loading constraints (3L-VRP).

The 3L-CVRP was introduced by Gendreau et al. (2006) with five additional packing constraints frequently occurring in freight transportation. These include a last-in-first-out (LIFO) loading constraint, a weight constraint, an orientation constraint, a support constraint, and a stacking constraint (see Section 3 for details). Gendreau et al. suggest a two-stage tabu search algorithm for solving the 3L-CVRP. The “outer” tabu search serves for planning the routes, while the “inner” tabu search solves a 3D strip packing problem in order to load a vehicle according to a given customer sequence. Tarantilis, Zachariadis, and Kiranoudis (2009) propose a hybrid procedure combining the strategies tabu search and guided local search. They use a collection of plain packing heuristics. Fuellerer, Doerner, Hartl, and Iori (2010) develop an ant colony algorithm for routing that is integrated with fast but effective packing heuristics. Wang, Guo, Chen, Zhu, and Lim (2010) design a two-phase tabu search algorithm for routing that cooperates with two constructive packing heuristics (see also Zhu, Qin, Lim, & Wang, 2012). Wisniewski, Ritt, and Buriol (2011) propose a tabu search for routing and a randomized bottom left-based packing algorithm. Bortfeldt (2012) suggests a hybrid algorithm for the 3L-CVRP with a tabu search procedure for routing and a tree search algorithm for loading vehicles. Ruan, Zhang, Miao, and Shen (2013) present a honey bee mating algorithm for routing that is combined with six loading heuristics. Lacomme, Toussaint, and Duhamel (2013) propose an effective hybrid procedure for the 3L-CVRP that, however, does not consider all 3D packing constraints introduced by Gendreau et al. (2006). Tao and Wang (2015) developed a tabu search procedure and hybridized it with an effective packing