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Solving the pickup and delivery problem with three-dimensional loading constraints and reloading ban

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ABSTRACT

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 set of rectangular boxes and the vehicle capacity is replaced by a 3D loading space.

This paper is the second one in a series of articles on 3L-PDP. As in the first paper we are dealing with constraints which guarantee that no *re*loading effort will occur. Here the focus is laid on the reloading ban, a packing constraint that ensures identical placements of same boxes in different packing plans. The reloading ban allows for better solutions in terms of travel distance than a routing constraint that was used in the first paper to preclude any reloading effort. To implement this packing constraint a new type of packing procedure is needed that is capable to generate a series of interrelated packing plans per route. This packing procedure, designed as tree search algorithm, and the corresponding concept of packing checks is the main contribution of the paper at hand. The packing procedure and a large neighborhood search procedure for routing form a hybrid algorithm for the 3L-PDP. Computational experiments were performed using 54 3L-PDP benchmark instances.

1. Introduction

This paper is the second one in a series of papers on the pickup and delivery problem with 3D loading constraints (3L-PDP). It continues the paper by Männel and Bortfeldt (2016), henceforth called first paper. We extend the classical PDP to an integrated routing and 3D loading problem. The PDP is defined in Parragh, Doerner, and Hartl (2008); a very recent survey on routing problems with loading constraints can be found in Pollaris et al. (2015). Apart from that we refer the reader to the literature review given in the first paper.

The 3L-PDP can roughly be described as follows. We are given a set of requests and a homogeneous fleet of vehicles. A set of routes, each starting and ending at the single depot, has to be determined such that each request is transported from a loading site to the corresponding unloading site and the total travel distance is minimized. 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. Each route has to be completed by a series of packing plans, where a packing plan represents an arrangement of boxes after having visited a pickup or delivery node. Besides basic geometrical constraints (e.g. no overlapping boxes) specific packing constraints as usual in VRP with 3D loading constraints (e.g. support condition) are to be satisfied.

Our main concern in the problem formulation of 3L-PDP is to guarantee that in 3L-PDP solutions any *re*loading effort can be excluded. That is, the boxes should not be moved *after* they were loaded and *before* they are unloaded. In the first paper necessary and sufficient conditions to avoid any reloading effort have been discussed. The results can be summarized as follows:

- It is assumed that boxes are loaded and unloaded at the rear of vehicles. Furthermore, boxes have to be loaded and unloaded by pure movements in length direction as usual in routing problems with 3D loading constraints (see Gendreau et al., 2006).
- First, we must require the request sequence (RS) constraint at delivery and pickup points of a route. At a delivery point, the RS constraint says that between a box A to be unloaded and the rear there is no box B to be unloaded later. Moreover, a box B to be unloaded later must not lie above box A. At a pickup point, the RS constraint requires that between a box A just loaded and

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Table 1
Five 3L-PDP variants (y: yes, n: no, a: automatically).

#	RS loading	RS unloading	Reloading ban	Independent partial routes	Reloading effort	Travel distance
1	y	n	n	n	High	Very low
2	y	y	n	n	Medium	Low
3	y	n	y	n	Medium	Low
4	y	y	y	n	Zero	Medium
5	y	a	a	y	Zero	High

the rear or above box A there is no box B that was loaded at an earlier pickup point. If the RS constraint would not be satisfied at a delivery or pickup point, boxes could not be unloaded or loaded by a pure movement in length direction and without moving other boxes. For a delivery point, placements of other boxes would have to be changed temporarily in order to unload boxes with this destination by pure length shifts. For a pickup point, placements of other boxes must be changed temporarily to reach the final positions for the loaded boxes by pure length movements.

- However, the RS constraint is not sufficient to avoid any reloading effort. In a route for 3L-PDP, generally boxes of a request A are transported for a part of the route together with boxes of a request B and for another part together with boxes of a request C (and no longer with boxes of B) etc. Packing plans have to be provided for all parts of the route in which different sets of boxes are transported. If different packing plans are provided for the boxes of a request A, because the boxes are first to be packed with the boxes of request B and then with the boxes of request C, the placements of the boxes of A may change. This would not necessarily violate required packing constraints. Thus there would exist feasible 3L-PDP solutions including boxes that are to be *re*loaded after loading and before unloading; an elaborated example is shown in the first paper.
- To rule out any reloading effort, we have to specify an extra constraint. There are two options to do so, i.e. we can introduce an additional routing constraint and, alternatively, we can define a packing constraint that rules out any reloading effort.
- The mentioned routing constraint, called independent partial routes (IPR) constraint, rules out any reloading effort by restricting the shape of the routes, i.e. in an implicit fashion. This is done by so-called 3L-PDP routing patterns, which ensure that the boxes of any request are not stored together with boxes of different requests in different parts of a route.
- The additional packing constraint, termed reloading ban, requires that the placement of any box, including the position of a reference corner (or of the geometrical midpoint) and the spatial orientation of the box, must not undergo a (permanent) change after the box has been loaded and before the box is unloaded. The reloading ban is tailored to the general shape of 3L-PDP routes: it forbids explicitly a change of placements of boxes of a request A if they are loaded together with boxes of a request C after they have been loaded together with boxes of a request B.

In the first paper we have introduced a spectrum of five 3L-PDP variants (see Table 1). The RS constraint at pickup points (denoted by (C1)) is always required. The variants are specified by means of the RS constraint for delivery points (C2), the reloading ban (C3) and the IPR constraint (C4). For each variant and constraint the entry is “y” if the constraint is to be met and “n” if not. If the IPR condition and the RS constraint at pickup points are required, RS constraint at delivery points and reloading ban are automatically satisfied; this is marked by entry “a”.

We consider variants 4 and 5 as the main 3L-PDP variants. In both variants any reloading effort is excluded by different means, namely by a routing constraint (variant 5) or a packing constraint (variant 4). The main 3L-PDP variants correspond to practical scenarios where a reloading of goods is not a viable option. This can be the case for different reasons, e.g. lack of manpower and equipment or narrow space at customer sites.

However, we also deal with three variants (1–3) where reloading effort is not excluded a priori. In this way we want to study the “costs” of avoidance of reloading effort in terms of travel distance. Generally, we expect a trade-off between travel distance and reloading effort. Thus, in the last two columns of Table 1 the expected reloading effort and expected (total) travel distance are indicated.

Moreover, the problem variants 1–3 might also have some practical relevance. If pickup and delivery transports are to be organized in rural areas with great distances between customers it could be advantageous to accept some reloading effort and to save a large travel distance in return (see Xu, Chen, Rajagopal, & Arunapuram, 2003).

The different 3L-PDP variants are illustrated by some (two-dimensional) single route examples in Fig. 1. The node number 0 denotes the depot while Pi and Di ($i = 1, \ldots, 4$) stand for the pickup and delivery nodes. For all nodes the state of the loading space is shown after the loading/unloading operation at the corresponding node has taken place (view from above). In all examples the driver’s cabin is on left and the loading door on the right side of the loading space. In the example for variant 1 for unloading the box I11 at node D1 it is necessary to unload the box I21 first; furthermore the box I21 is reloaded at another position to allow the loading of the boxes I31 and I32 at the following node P3. So neither the RS unloading constraint (C2) nor Reloading ban constraint (C3) is satisfied here. In the example for variant 2 the RS unloading constraint (C2) is satisfied at all delivery nodes but Reloading ban constraint (C3) is not satisfied because the placement of box I12 is changed permanently at P3 to allow the loading of box I31. In the example for variant 3 for unloading the box I11 at node D1 again it is necessary to unload the box I21 first (like in the first example), but now the box I21 is reloaded at the same position, so Reloading ban constraint (C3) is satisfied and only RS unloading constraint (C2) is unsatisfied here. In the example for variant 4 both RS unloading constraint (C2) and Reloading ban constraint (C3) are satisfied, especially the boxes I11 and I12 hold the same placements at nodes P2 and P3 (interrelated packing plans). In the last example for variant 5 the special structure of a route which complies the IPR constraint (C4) is shown. First some pickup points are visited and then all corresponding delivery points follow in inverse order. If one delivery node has been visited a further pickup is only allowed when all boxes are unloaded before. In the example this situation occurs when the vehicle leaves node D3 and goes to pickup node P4.

A precise formulation of the 3L-PDP (including all above variants) with constraints (C1)–(C10) can be found in the first paper. For convenience a short description of constraints (C5)–(C10), not mentioned before, is given in Table 2.

In the first paper the focus was laid on problem variants 1, 2 and 5. *In the second paper we deal with variants 3 and 4.* In variant 5 any reloading effort is excluded by strongly restricting the admitted routes and this will have a negative impact on travel distances. In the 3L-PDP variant 4 there is no restriction of vehicle routes. Instead the reloading ban (C3) is in charge to preclude any reloading effort and better travel distances can be expected. To implement this packing constraint a new type of packing procedure is needed that is capable to generate a series of interrelated packing plans per route (see above example). The design of this packing procedure and the corresponding concept of packing checks is the main contribution of the paper at hand. In the 3L-PDP variant 3 the RS