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The pickup and delivery traveling salesman problem with handling costs

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ABSTRACT

This paper introduces the pickup and delivery traveling salesman problem with handling costs (PDTSPH). In the PDTSPH, a single vehicle has to transport loads from origins to destinations. Loading and unloading of the vehicle is operated in a last-in-first-out (LIFO) fashion. However, if a load must be unloaded that was not loaded last, additional handling operations are allowed to unload and reload other loads that block access. Since the additional handling operations take time and effort, penalty costs are associated with them. The aim of the PDTSPH is to find a feasible route such that the total costs, consisting of travel costs and penalty costs, are minimized. We show that the PDTSPH is a generalization of the pickup and delivery traveling salesman problem (PDTSP) and the pickup and delivery traveling salesman problem with LIFO loading (PDTSPL). We propose a large neighborhood search (LNS) heuristic to solve the problem. We compare our LNS heuristic against best known solutions on 163 benchmark instances for the PDTSP and 42 benchmark instances for the PDTSPL. We provide new best known solutions on 52 instances for the PDTSP and on 15 instances for the PDTSPL, besides finding the optimal or best known solution on 102 instances for the PDTSP and on 23 instances for the PDTSPL. The LNS finds optimal or near-optimal solutions on instances for the PDTSPH. Results show that PDTSPH solutions provide large reductions in handling compared to PDTSP solutions, while increasing the travel distance by only a small percentage.

1. Introduction

In this paper, we introduce, model and solve the pickup and delivery traveling salesman problem with handling costs (PDTSPH). In the PDTSPH, a single vehicle based at a central depot must fulfill a set of requests. Each request determines the transportation of items from a specific pickup location, where the items are loaded into the vehicle, to a specific delivery location, where the items are unloaded from the vehicle. We consider a rear-loaded vehicle with a single (horizontal) stack that is operated in a last-in-first-out (LIFO) fashion. At a pickup location, items are placed on top of the stack. At a delivery location, if an item is not on top of the stack, there are items on top blocking the access, and handling operations are required to unload and reload the items that blocked the access. Since the additional handling operations of unloading and reloading items take time and effort, penalty costs are associated with them. Fig. 1 shows two feasible routes, in which route (Fig. 1a) requires no additional handling, whereas in route (Fig. 1b) an additional handling operation is needed to move item 3 upon delivery of item 2. The aim of the PDTSPH is to find a feasible route such that the total costs, consisting of travel costs and penalty costs, are minimized.

The PDTSPH as presented here arises in the transportation of less-than-truckload items, and is especially faced by freight transportation companies responsible for transporting large items that are easy to load and unload, such as cars. A typical challenge for these companies is to define a route along all customers by finding a trade-off between travel costs and additional handling operations. Minimizing travel costs can result in routes with a large number of additional handling operations, whereas minimizing the additional handling operations may result in sub-optimal routes with respect to the travel distance. Therefore, it is relevant for these companies to simultaneously take both aspects into account when generating a vehicle route.

To our knowledge, the PDTSPH has not yet been studied in literature. Related is the research of Battarra, Erdoğan, Laporte, and Vigo (2010) and Erdoğan, Battarra, Laporte, and Vigo (2012). They propose exact and heuristic methods for a problem that considers requests that either originate from or destinate to the depot. This implies that all loads destined to customers are already in the

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$$0 \to 1^{+} \to 2^{+} \to 2^{-} \to 3^{+} \to 3^{-} \to 1^{-} \to 0$$

(a)

$$0 \to 1^{+} \to 2^{+} \to 3^{+} \to 2^{-} \to 3^{-} \to 1^{-} \to 0$$

(b)

Fig. 1. Two feasible routes, in which route (a) does not require any additional handling operations and route (b) requires an additional handling operation. In the figure, i^+ and i^- correspond to the pickup and delivery location of request i, respectively.

vehicle at the start of the route, and all loads originating from customers are in the vehicle at the end of the route.

The PDTSPH is a generalization of two problems, as we will prove in Section 3, namely the pickup and delivery traveling salesman problem (PDTSP), and the pickup and delivery traveling salesman problem with LIFO loading (PDTSPL). The aim of the PDTSP is to find a vehicle route that fulfills all requests and minimizes transportation costs. Additional handling operations are not considered in the PDTSP. Exact and heuristic methods have been proposed for the PDTSP. Savelsbergh (1990) describes different local search algorithms, Healy and Moll (1995) propose an extension of traditional improvement algorithms, and Renaud, Boctor, and Ouenniche (2000) develop a two-stage heuristic consisting of a construction phase and a deletion and reinsertion phase. Different perturbation heuristics are proposed by Renaud, Boctor, and Laporte (2002) and Dumitrescu, Ropke, Cordeau, and Laporte (2010) present a branch-and-cut algorithm. For the pickup and delivery vehicle routing problem, a variant of the PDTSP that considers multiple vehicles, we refer to Bent and Hentenryck (2006), and Ropke and Pisinger (2006). The aim of the PDTSPL is to find a vehicle route that completes all requests and minimizes transportation costs, while prohibiting additional handling operations. This implies that a vehicle can only visit a delivery location if the corresponding item is on top of the stack. Exact and heuristic methods have been proposed for the PDTSPL. Cassani and Righini (2004) propose a variable neighborhood descent heuristic, Carrabs, Cordeau, and Laporte (2007b) introduce a variable neighborhood search (VNS) heuristic, Carrabs, Cerulli, and Cordeau (2007a) propose a branch-and-bound algorithm, Cordeau, Iori, Laporte, and Salazar González (2010) develop a branch-and-cut algorithm, Li, Lim, Oon, Qin, and Tu (2011) present a VNS heuristic based on a tree representation, Côté, Gendreau, and Potvin (2012) describe a large neighborhood search heuristic, and Wei, Qin, Zhu, and Wan (2015) propose a VNS with a different perturbation operator. We refer to Cherkesly, Desaulniers, and Laporte (2015) and Benavent, Landete, Mota, and Tirado (2015) for the pickup and delivery problem with LIFO loading, a variant of the PDTSPL that considers multiple vehicles.

The contribution of our paper is fourfold: (1) we formally describe and formulate the PDTSPH, (2) we prove that the problem is a generalization of the PDTSP and of the PDTSPL, and (3) we derive a heuristic solution method to efficiently solve the problem and its special cases. Namely, we propose a large neighborhood search (LNS) metaheuristic, that includes new removal operators, and is shown to provide good quality solutions. (4) As a part of extensive computational results on benchmark instances for the PDTSP, the PDTSPL, and for the newly defined PDTSP, we provide new best known solutions on 52 instances for the PDTSP and on 15 instances for the PDTSPL.

The remainder of this paper is structured as follows. In Section 2, we develop a binary integer programming formulation for the PDTSPH. In Section 3, we prove that the PDTSPH is a generalization of the PDTSP and the PDTSPL. Section 4 describes the proposed LNS heuristic. Section 5 reports the experimental setting and the results of extensive computational experiments performed on the three classes of problems, followed by conclusions in Section 6.

2. Mathematical formulation

The PDTSPH is defined on a directed graph $G = (V, A)$, where V is the set of nodes and A is the set of arcs. Let n be the number of requests. The set of nodes is given by $V = \{0, 1, \ldots, 2n\}$, where 0 corresponds to the depot, $P = \{1, \ldots, n\}$ is the set of pickup nodes, and $D = \{n+1, \ldots, 2n\}$ is the set of delivery nodes. Let $V' = V \setminus \{0\}$ be the set of nodes excluding the depot, and let A' be the subset of arcs having both endpoints in V'. Each request i is associated to a pickup node $i \in P$ and a delivery node $(n+i) \in D$, graphically denoted by i^+ and i^-, respectively. For convenience, we also refer to the set P as the set of requests. Each request corresponds to the transportation of one item. The travel cost of arc $(i, j) \in A$ corresponds to the travel distance and is given by c_{ij}. We assume that c_{ij} satisfies the triangle inequality. An additional handling operation consists of unloading and reloading an item at a location. We only allow an item to be unloaded and reloaded when it is blocking the delivery operation, i.e., if an item is on top of the item to be delivered. We assume that the reloading sequence is the inverse of the unloading sequence, i.e., the relative positions of the items remain the same. This limitation will be lifted at a later point in the paper. The penalty cost associated to an additional handling operation is fixed and given by h. The number of handling operations corresponding to loading the items at their pickup locations and unloading them at their delivery locations is constant and cannot be avoided. Therefore, without loss of generality, in our formulation no penalty costs are associated to them.

The flow based formulation of the binary integer program for the PDTSPH is based on the model of Erdoğan, Cordeau, and Laporte (2009) for the PDTSP. Let x_{ij} be a binary variable equal to one if and only if arc $(i, j) \in A$ is traveled by the vehicle. Let y^1_{ijk}, y^2_{ijk} and y^3_{ijk} be three binary flow variables. Variable y^1_{ijk} is equal to one if and only if arc $(i, j) \in A$ is on the partial path from node 0 to node k; variable y^2_{ijk} is equal to one if and only if arc $(i, j) \in A$ is on the partial path from node k to node $n+k$; variable y^3_{ijk} is equal to one if and only if arc $(i, j) \in A$ is on the partial path from node $n+k$ to node 0. We introduce binary variables r_{kl}, $\forall k \in P$, $l \in D$, equal to one if and only if item k is unloaded and reloaded at delivery node l. The total number of handling operations at delivery node $l \in D$ is equal to $\Sigma_{k \in P} r_{kl}$, which is equal to the number of items that block access, i.e., all items on top of item $l-n$ in the stack. Then, the PDTSPH is formulated as:

$$\min \quad \sum_{(i,j)\in A} c_{ij} x_{ij} + h \sum_{k\in P} \sum_{l\in D} r_{kl} \tag{1}$$

$$\text{s.t.} \quad \sum_{j:(i,j)\in A} x_{ij} = 1 \quad \forall i \in V \tag{2}$$

$$\sum_{i:(i,j)\in A} x_{ij} = 1 \quad \forall j \in V \tag{3}$$