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Innovative Applications of O.R.

The multi-pickup and delivery problem with time windows

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ABSTRACT

This paper investigates the multi-pickup and delivery problem with time windows in which a set of vehicles is used to collect and deliver a set of items defined within client requests. A request is composed of several pickups of different items, followed by a single delivery at the client location. We formally describe, model and solve this rich and new problem in the field of pickup and delivery vehicle routing. We solve the problem exactly via branch-and-bound and heuristically developing a hybrid adaptive large neighborhood search with improvement operations. Several new removal and insertion operators are developed to tackle the special precedence constraints, which can be used in other pickup and delivery problems. Computational results are reported on different types of instances to study the performance of the developed algorithms, highlighting the performance of our heuristic compared to the exact method, and assessing its sensibility to different parameter settings.

1. Introduction

In many applications, vehicles must perform several sequential pickups of one or different commodities, and once all pickups are performed, the vehicle must deliver all of them to a given location. This type of problem arises, for example, in the collection of cash from parking tolls: an employee leaves the depot with a key that only allows access to the cash of some tolls to be dropped in a given delivery location. He can then visit the tolls in any order, but must visit them all before delivering all the cash, which must happen before he can have access to another key. This multi-pickup and delivery problem also appears for companies that allow a client to order food from different restaurants; the company must then perform all pickups at different places, before delivering all meals to the client location. Examples of companies operating under this setting are *JUST EAT*, *Uber eats* and *SkipTheDishes*. These applications impose not only a partial ordering of the visits (all pickups prior to the delivery), but also that all stops associated to a single request must be performed by the same vehicle.

In this paper we consider a multi-pickup and delivery problem with time windows (MPDPTW), in which a set of requests is satisfied by a fleet of vehicles. In each request, items are required to be picked up from different locations to be shipped and unloaded at one common delivery location. In addition, a time window (TW) is associated with each node, such that pickups and deliveries can only be performed within the node's start and end times. The depot at which the vehicles are also housed contain TWs representing its opening hours. The goal is to obtain feasible vehicle tours fulfilling the requests for pickups and deliveries, while minimizing the overall costs associated with the routing of a set of requests.

In the MPDPTW, a request must be fulfilled by a single vehicle. This means that all pickups and the corresponding delivery must be performed by a single tour, possibly combined with other requests. Moreover, vehicle tours have to be developed with respect to precedence constraints, while reducing the overall routing cost. The precedence constraints are related to the order in which nodes of a given request are visited. These constraints do not incur a direct precedence between the last visited pickup and delivery nodes. It is rather required for a vehicle fulfilling a given request to visit all its pickup locations before reaching the corresponding delivery node.

The MPDPTW shares some characteristics with problems previously studied in the literature, namely the pickup and delivery problem with time windows (PDPTW) and the sequential ordering problem (SOP). These are briefly reviewed next.

According to the review and classification of Berbeglia, Cordeau, Gribkovskaia, and Laporte (2007), our problem lies in the family of many-to-many pickup and delivery, in which a request is associated with a pickup node and a delivery node. This differs from the one-to-many in which the origin of all commodities is the depot, and the many-to-one in which all deliveries are headed to the depot. However, in classical many-to-many problems, a request consists of a pair origin-destination. In the MPDPTW, many compulsory origins are associated with a single delivery, and all

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origins must be visited (in no particular order) prior to the delivery. We note, however, that existing algorithms for pickup and delivery problems cannot solve an instance of the MPDPTW due to the added complexity of handling multiple pickups for a single request.

Approximate algorithms for the pickup and delivery problem include the adaptive large neighborhood search of Pisinger and Ropke (2007), the parallel neighborhood descent of Subramanian, Drummond, Bentes, Ochi, and Farias (2010), and the particle swarm optimization of Ai and Kachitvichyanukul (2009); Goksal, Karaoglan, and Altiparmak (2013). Exact algorithms for the pickup and delivery with TWs include the branch-and-cut of Ropke, Cordeau, and Laporte (2007), the branch-cut-and-price of Ropke and Cordeau (2009) and the set partitioning-based algorithm of Baldacci, Bartolini, and Mingozzi (2011). A number of variants of the problem exists, as it is used to represent many real-life distribution problems (Coelho, Renaud, & Laporte, 2016).

A similar problem is the SOP, which consists of building a Hamiltonian path in order to solve the asymmetric traveling salesman problem (ATSP) with precedence constraints: the visit of a given node has to be done after visiting a required set of direct and/or indirect predecessors. The SOP differs from the pickup and delivery problem as a node can have multiple direct predecessors (Alonso-Ayuso, Detti, Escudero, & Ortuño, 2003; Guerriero & Mancini, 2003). Moreover, a single node can be the direct predecessor of several other nodes, resulting into a tree-like route structure. This problem was introduced in Escudero (1988) to design heuristics for production planning systems. It has been extended into the constrained SOP (CSOP) (Escudero & Sciomachen, 1993) to include additional precedence relationships between nodes, such as TWs, where a release date and a deadline are associated with each visited node. The SOP is used to model real-world problems within production planning in flexible manufacturing systems and for vehicle routing and transportation problems (Ezzat, Abdelbar, & Wunsch, 2014). It has been applied to helicopter routing, job sequencing in flexible manufacturing, stacker cranes in automatic storage systems (Ascheuer, Jünger, & Reinelt, 2000), single vehicle routing with pickup and delivery constraints (Fiala Timlin & Pulleyblank, 1992; Savelsbergh, 1990), multicommodity one-to-one pickup and delivery TSP problems (Gouveia & Ruthmair, 2015; Hernández-Pérez & Salazar-González, 2009) and dial-a-ride problems in which items or people are picked up at some points and delivered to others (Balas, Fischetti, & Pulleyblank, 1995). According to Desaulniers, Desrosiers, Erdmann, Solomon, and Soumis (2001) a variety of techniques based on restrictions, e.g., precedence constraints, are used in order to reduce the network size. Several approaches have been adopted to solve the SOP. Savelsbergh (1990) developed local search algorithms based on the k-exchange concept. Balas et al. (1995) used time separation algorithms for solving problems arising in both scheduling and delivery routing problems. Ascheuer et al. (2000) used an integer program solved by a branch-and-cut. Guerriero and Mancini (2003) proposed a sequential solution approach through a parallel version of the heuristic rollout algorithm, while Seo and Moon (2003) adopted a hybrid genetic algorithm. Alonso-Ayuso et al. (2003) used a lagrangian relaxation-based scheme for obtaining lower bounds on the optimal solution. Finally, Letchford and Salazar-González (2016) provided a multi-commodity flow formulation for the SOP and the CSOP.

While the MPDPTW is associated with many model characteristics of existing distribution problems, to our knowledge, this problem has not received any attention in the literature. In this paper we introduce a formal problem formulation of MPDPTW taking into account its complicating multi-pickup characteristics. Moreover, each vehicle route in a MPDPTW can be interpreted as an ATSP, in which the distance between two nodes is different depending on the sequence in which the nodes are visited. For example given two locations l_1 and l_2, the travel time from l_1 to l_2 may be different from the travel time from l_2 to l_1. Given the precedence constraints on request nodes and on vehicle start and end depots, the vehicle routes are similar to a constrained ATSP. We solve this formulation by branch-and-bound using a commercial solver, capable of proving optimality for small instances and providing bounds for larger ones. Moreover, we exploit the ALNS framework to design and implement an algorithm tailored for the MPDPTW. We propose new removal and insertion operators handling the multi-pickup characteristics of the requests defined within the problem. These operators are also new in the literature and can help solve other types of similar problems, being adapted for the TOP or the ATSP with precedence constraints. Promising solutions are also polished using local search operators within our heuristic framework.

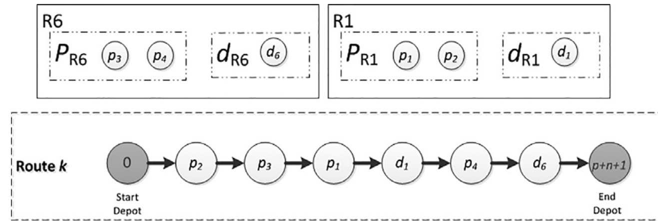

Fig. 1. Requests R1 and R6 inserted into route k.

The remainder of this paper is organized as follows. Section 2 describes MPDPTW and introduces a mathematical programming formulation. The general heuristic framework based on a hybrid ALNS method is presented in Section 3, including the new request insertion procedure. Computational results are reported in Sections 4 and 5 concludes the paper with main findings and future research avenues.

2. Problem description

A problem instance of the MPDPTW contains n requests and m vehicles. Let $P = \{1, \ldots, p\}$ be the set of pickup nodes, and $D = \{p+1, \ldots, p+n\}$ be the set of delivery nodes where $|D| = n$ and $p \geq n$. Let $R = \{r_1, \ldots, r_n\}$ be the set of requests to be routed. Each request $r \in R$ is represented by a set of pickup nodes $P_r \subseteq P$ and a delivery node $d_r \in D$. Each pickup node belongs to exactly one set, and each request always contains at least one pickup node. Let $N = P \cup D$ be the set of customer nodes. Let $r(i)$ be the request associated with node $i \in N$. Let $K = \{1, \ldots, m\}$ be the set of available vehicles.

The graph $G = (V, A)$ consists of the nodes $V = N \cup \{0, p+n+1\}$ where 0 and $p+n+1$ are the starting and ending depot. Each node $i \in V$ has a service time s_i and a TW $[a_i, b_i]$. Given the TW, a vehicle can arrive at node i earlier than the start of its TW a_i, having to wait until a_i to start the service. Moreover, a vehicle must arrive at node i before b_i, such that the service at node i starts within its TW.

The set of arcs is $A = V \times V$ minus arcs that lead to infeasible solutions: we omit arc (i, j) if i is a pickup node and j is its delivery node if $b_j < a_i + s_i + t_{ij}$. A distance $d_{ij} \geq 0$ and a travel time $t_{ij} \geq 0$ are associated with each arc $(i, j) \in A$. Let $A^+(i)$ and $A^-(i)$ be the sets of outgoing and incoming arcs from node $i \in V$.

Fig. 1 illustrates two requests $R1$ and $R6$ and a route associated with vehicle k. For example in $R6$ two pickups nodes p_3 and p_4 have to be visited to collect items to be delivered to d_6. $R1$ and $R6$ are inserted in route k where precedence constraints are respected. Note that node p_1 is not directly visited after p_2 from the same request. Moreover, the delivery node of request R_1 is visited after