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Failure-specific cooperative recourse strategy for simultaneous pickup and delivery problem with stochastic demands

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ABSTRACT

This paper concerns the generation of a priori routes for a fleet of vehicles that pick up and deliver items with stochastic demands. A failure-specific cooperative recourse strategy is proposed to explore a risk pooling mechanism for routing in the context of simultaneous pickup and delivery with stochastic demands. By defining complete failure and semi-failure of routing, the travelling cost under our failure-specific cooperative strategy is estimated. Also, an adaptive large neighbourhood search algorithm is developed. Compared with a strategy that involves no cooperation between vehicles, our strategy performs better in terms of reducing travelling costs, and balancing fleet size and detour frequency.

1. Introduction

The vehicle routing problem with simultaneous pickup and delivery (VRPSPD) is an extension of the classic vehicle routing problem (VRP). In the VRPSPD, a vehicle departs from the depot, picks up items from and simultaneously delivers goods to customers, and finally returns to the depot (Berbeglia, Cordeau, Gribkovskaia, & Laporte, 2007; Berbeglia, Cordeau, & Laporte, 2010; Polat, Kalayci, Kulak, & Günther, 2015). The picked up and delivered items are regarded as two types of products: the picked up items are referred to as returned (recycled or retired), while the delivered items are new products. This problem is also relevant to reverse logistics (Dell'Amico, Righini, & Salani, 2006; Nagy, Wassan, Speranza, & Archetti, 2015).

This paper studies the VRPSPD with stochastic demands (SD), denoted *simultaneous pickup and delivery problem with stochastic demands* (SPDPSD), referring to the situation where customer demand for pickup or delivery is stochastic (or both). Under the SPDPSD, a vehicle may reach a customer location without enough capacity to pick up returned items or sufficient inventory to deliver new products (or both). This causes a route *failure* that requires a *recourse* action. Various recourse actions are possible (Zhu, Rousseau, Rei, & Li, 2014): (i) replenishing the vehicle at the depot, (ii) scheduling another vehicle to visit the customer where the failure occurred, and (iii) skipping the customer altogether (a penalty is incurred in this case). We consider (i) and (ii), situations in which a driver performs a detour trip to the depot or leaves the demand to be satisfied by another driver.

Research relevant to the SPDPSD is scant when considering restocking policies (e.g., Dimitrakos & Kyriakidis, 2015; Minis & Tatarakis, 2011; Pandelis, Karamatsoukis, & Kyriakidis, 2013; Pandelis, Kyriakidis, & Dimitrakos, 2012) or routing decisions (e.g., Hou & Zhou, 2010; Hu, Sheu, Zhao, & Lu, 2015), and few works pay attention to the construction of a priori routes. To the best of our knowledge, only Wollenberg (2015) observed this gap and studied a situation where delivery demand was known with certainty. We deal with the SPDPSD when all customer demands are stochastic, and we generate a priori routes for simultaneous pickup and delivery with uncertain demands.

To obtain a priori routes, stochastic programming with recourse (SPR) is often used. The travelling cost of a route is approximated by the total of the cost of the planned route and the cost of expected recourse actions (e.g., Laporte, Louveaux, & Van Hamme, 2002). Ak and Erera (2007) proposed a recourse strategy, named paired locally-coordinated (PLC), which followed the SPR standard and embedded locally-coordinated mechanism. PLC reduces the travelling cost through vehicle cooperation. Using the PLC, each vehicle in a pair serves customers sequentially, following a fixed route. If one vehicle fails, it ceases its service immediately and all unserved customers are assigned to its partner (see Ak & Erera, 2007). But this strategy is not applicable to the problem that we concern. In the SPDPSD, route failure may be frequent (due to insufficient capacity for a pickup or inventory for a delivery). If the PLC strategy is followed, frequent and undesired vehicle interac-

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tion may occur; a vehicle may fail and cease service at the first customer and put all remaining burdens on its partner.

We propose a cooperative recourse strategy that is applicable to the SPDPSD. In our strategy, if a vehicle fails, it resumes its route to serve its remaining assigned customers, rather than leaving all of them to its partner.

We identify two kinds of failure for a vehicle serving customers with pickup and delivery demand. The first type of failure is called *complete-failure* (CF or C-failure), and it refers to the case where a vehicle is fully loaded with returned items; in this case, the vehicle, with neither capacity for a pickup nor new products for delivery, has to unload and reload at the depot before resuming its route. The second type of failure is *semi-failure* (SF or S-failure); in this case, there is still either sufficient capacity for a pickup at or inventory for delivery to another customer, and the vehicle need not return to the depot.

The development of our *failure-specific cooperative recourse* (FSC) strategy is based on these two types of failure. Each pair of vehicles is composed of a lead vehicle and a partner vehicle; the lead vehicle follows a fixed route to serve its customers, and the partner vehicle is scheduled to assist the lead vehicle in completing its service while also serving its own assigned customers. The benefit of letting the partner vehicle take over is greatest, when the depot is distant and the partner vehicle is near the lead vehicle.

The probabilities of C-failure and S-failure are used in computing the total expected travelling cost. Given recourse actions in FSC strategy, the probability of C-failure is used to compute the expected recourse cost of the lead vehicle, and the probability of S-failure is relevant to the possibility of the partner vehicle visiting a customer in order to satisfy the customer's remaining demand.

This paper's main contribution is the development of an FSC strategy to build a priori routes for simultaneous pickup and delivery. When a C-failure or S-failure is encountered, this strategy informs the lead vehicle to satisfy unmet demand after returning to the depot or leave unmet demand to its partner vehicle. We compute the expected travelling cost of each vehicle that follows an a priori route and takes recourse actions according to FSC strategy. We develop an adaptive large neighbourhood search (ALNS) algorithm that optimises routing sequences. We compare the performance of FSC strategy (through a numerical study that shows its benefit in terms of both real travelling costs and in the balance of fleet size and detour frequency) to that of another recourse strategy.

The remainder of this paper is organised as follows: Section 2 describes the problem we concern; Section 3 illustrates FSC strategy; Section 4 estimates the expected cost of a pair of routes; Section 5 presents the ALNS algorithm; and Section 6 compares FSC strategy with another recourse strategy and discusses relevant numerical results.

2. Problem description and notations

Consider a complete network, and let the set of nodes be $\{0, 1, \ldots, N\}$, where N is a positive integer. Node 0 denotes the depot and $C = \{1, \ldots, N\}$ is the set of customers. The travelling distance $d(i, j)$ between any nodes i and j is symmetric and satisfies the triangular inequality. A fleet of vehicles with identical capacity Q operates to meet pickup and delivery demands. The number of vehicles in use is determined by the operator, with sufficient vehicles in the fleet. Assume that customer demands are identically distributed, and ξ_i and φ_i $(i = 1, \ldots, N)$ are the discrete random variables that describe the amount of delivered and picked up items demanded by customer i. The probability mass functions are $q(e) = \Pr\{\xi_i = e\},\ e = 0, 1, \ldots, Q$ and $h(t) = \Pr\{\varphi_i = t\},\ t = 0, 1, \ldots, Q$, respectively, where demands ξ_i and φ_i are mutually independent and observed only when a vehicle arrives. Each vehicle starts from the depot, serves its assigned customers following a predefined routing sequence, and eventually returns to the depot. The problem is to design the a priori route for each vehicle in use, and to reduce the total travelling cost.

Assume that a vehicle arrives at new customer i, it first delivers as many new products as possible to satisfy demand ξ_i, and then picks up the largest possible quantity of returned items to meet demand φ_i. After the first visit of customer i, the vehicle's inventory of new products is reduced to z_i, and its available capacity changes to r_i. z_i can be less than 0, indicating the quantity of new products still needed to complete delivery service to customer i, and $z_i^- = -\min\{0, z_i\}$ denotes the amount owed to be delivered. r_i can also be less than 0, indicating the quantity of returned items from customer i that cannot be loaded on the vehicle, and $r_i^- = -\min\{0, r_i\}$ denotes the amount owed to be picked up; when r_i is positive, it refers to the empty space that has not been occupied by any items, either returned or new products (i.e., $r_i = Q - \max\{z_i, 0\} - \{amountofreturneditemsafterloading\},\ \text{if } r_i > 0$).

Let $(z_i,\ r_i)$ denote the state of a vehicle after the first visit of customer i and the time that is used as the decision epoch for scheduling a vehicle to visit a new customer, either directly or via a detour trip to the depot. Ψ_i denotes the state set after the vehicle's first visit of customer i, i.e., $\forall (z_i,\ r_i) \in \Psi_i$. The cardinality of Ψ_i is $(2Q + 1)^2 - \frac{1}{2}Q(Q + 1)$, by enumerating the values of $(z_i,\ r_i)$ when requirements $z_i \in \{-Q, \ldots, Q\},\ r_i \in \{-Q, \ldots, Q\}$ and $z_i + r_i \le Q$ are satisfied. θ_i refers to the quantity of new products to be restocked at the depot after the vehicle completes its service of customer i.

Assume that a customer can be served by more than one vehicle. If a failure occurs at customer i, the vehicle should satisfy as much of the delivery and pickup demand of customer i as possible, before leaving the remainder of the demand to be satisfied by itself on a return trip or by another vehicle.

3. Failure-specific cooperative recourse strategy for the SPDPSD

FSC is a recourse strategy that allows cooperation between each pair of vehicles. A subset of customers is assigned to a pair of vehicles, and each customer is served by one or both of the vehicles. In each pair, the lead vehicle follows a type A route, serving each customer in turn; in the event of an S-failure, it proceeds to the next customer, and in the event of a C-failure it returns to the depot to unload and reload. Meanwhile, the partner vehicle follows a type B route, and meets any demand not met by the lead vehicle.

Let C_p $(\bigcup_p C_p = C)$ be the subset of customers that a pair of vehicles, V_A^p and V_B^p serve, where V_A^p and V_B^p follow type A and type B routes respectively, simply denoted by V_A and V_B. One example of a pair of vehicles travelling under FSC strategy is shown in Fig. 1.

Fig. 1(a) shows the a priori routes for a pair of vehicles. Fig. 1(b) shows that vehicle V_A follows a type A route, with C-failures at customer sites 2 and 8 and S-failures at customer sites 5 and 7; the vehicle proceeds to the next customer when an S-failure occurs and makes a detour trip to the depot when a C-failure occurs. In Fig. 1(c), customers 5 and 7 with unmet demands are revisited by the partner vehicle by adding those customers to the a priori type B route; the partner vehicle then meets the remaining customer demands altogether, making detour trips immediately after each subsequent failure, regardless of type.

Under FSC strategy, vehicle V_A, following a type A route, reacts differently depending on encountering a C-failure or an S-failure. With a C-failure, the vehicle is full of returned items and has to detour to the depot before resuming its route. Under this condition, the vehicle not only fails to meet the delivery demand of customer i (ξ_i), but also fails to satisfy the pickup demand of customer i (φ_i),