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The two echelon open location routing problem: Mathematical model and hybrid heuristic

Khosro Pichka[a], Amirsaman H. Bajgiran[b], Matthew E.H. Petering[b,*], Jaejin Jang[b], Xiaohang Yue[a]

[a] Sheldon B. Lubar School of Business, University of Wisconsin-Milwaukee, Milwaukee, WI 53201, USA
[b] Department of Industrial & Manufacturing Engineering, University of Wisconsin-Milwaukee, Milwaukee, WI 53201, USA

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ABSTRACT

Multi echelon distribution systems have become more common in recent years. This paper addresses the two echelon open location routing problem (2E-OLRP) which is a variant of the two echelon location routing problem (2E-LRP). This problem seeks to find a minimum-cost set of vehicle routes that do not return to the depot in the first echelon and do not return to satellites in the second echelon due to the presence of individual contractors and third party logistics (3PL) providers. In spite of the large amount of research on LRPs, the 2E-OLRP has received very little attention. Three flow-based mixed-integer linear programs and a hybrid heuristic algorithm are proposed to deal with this problem. Extensive experiments evaluate the effectiveness of these methods.

1. Introduction

There are two main categories of freight transportation with respect to the presence of one or more intermediate distribution facilities. Direct shipment is the delivery of products directly from the origin (i.e. depot) to customers. Indirect shipment includes shipments which pass through one or more intermediate facilities. In this paper, we consider a fright transportation problem that falls in the second category. In particular, we consider a variant of the two echelon location routing problem (2E-LRP). This problem is a core problem in supply chain network design, specifically in new city logistics, which analyzes two major decisions: the number and location of intermediate distribution depots (i.e. satellites) and the routing of vehicles in each echelon.

The two echelon open LRP (2E-OLRP) is a variant of the 2E-LRP in which each route in the first (second) echelon is a sequence of satellites (customers), that starts from a main depot (a satellite) and finishes at one of the satellites (customers) to whom goods are delivered by the available fleet. In contrast, in the classical 2E-LRP, all first (second) echelon vehicles return to the main depot (a satellite) after serving satellites (customers). In practice, the 2E-OLRP can arise when a supplier or producer does not have its own vehicle fleet or its fleet's capacity is not enough to serve all of its customers. Such a company may prefer to employ a third party logistics (3PL) provider to transfer goods between the depot, satellites, and customers. Indeed, from a supply chain management perspective, it may be more economical for such companies to outsource the distribution of their products. Thus, in the 2E-OLRP, the contractee does not need to have the fleet at its own depot after serving all the satellites or customers in a single planning horizon.

Recent trends have made the 2E-OLRP an increasingly important real-world problem. For example, the recent growth of e-commerce has dramatically increased the number of shipments from suppliers to individual customers, many of whom are located in densely populated urban areas. If the supplier has only one location or factory, it may be economical for the supplier to distribute product via a two-echelon (i.e. two-level) approach. In the first echelon, product is transported from the factory to distribution centers (satellites) on the outskirts of the cities in which product is demanded. In the second echelon, product is transported from the distribution centers to customers. Open routes are also becoming more commonplace. Indeed, the hiring of independent contractors and drivers to deliver packages in urban areas is becoming more widespread. Amazon Flex, which allows individual drivers to deliver packages from Amazon distribution centers to delivery points, has been launched in more than fifty cities across the United States (Amazon.com). Uber Rush is another example that shows the growing trend of outsourcing in urban transportation services (Uber.com).

An example of the 2E-OLRP, in which there is one main depot (triangle), four satellites (squares), and ten customers (circles), is illustrated in Fig. 1. The dashed arrows show the routes of two vehicles in the first echelon while the solid arrows show the routes of five vehicles that transport goods from opened satellites to customers in the second echelon.

As Fig. 1 shows, in the first echelon, a vehicle starts its route from

* Corresponding author.
E-mail addresses: kpichka@uwm.edu (K. Pichka), hamzehb2@uwm.edu (A.H. Bajgiran), mattpete@uwm.edu (M.E.H. Petering), jang@uwm.edu (J. Jang), xyue@uwm.edu (X. Yue).

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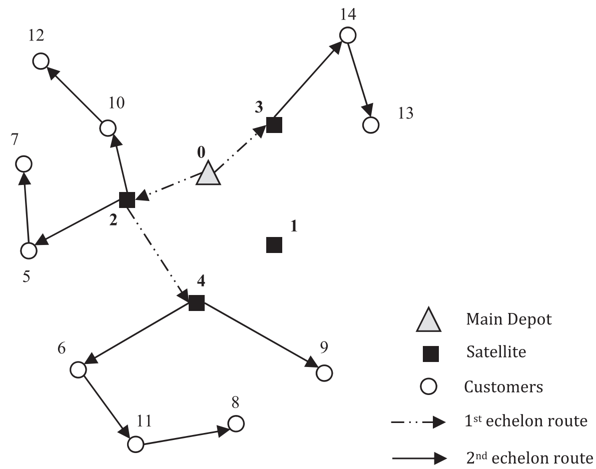

Fig. 1. Example of the 2E-OLRP.

the main depot and serves one or more satellites and finishes its route at a satellite. The demand of an opened satellite equals the total demand of customers which we decide to assign to that satellite. If a satellite is not opened, no customer is assigned to that satellite. On the other hand, a second echelon route starts from an opened satellite and ends at a customer after serving one or more customers. One should note that all the customer demands should be satisfied. The demands satisfied by a first (second) echelon route cannot exceed the capacity of a first (second) echelon vehicle. We assume that the demand of a satellite in the first echelon cannot be satisfied by more than one first-echelon vehicle. In other words, split deliveries are not allowed. Similarly, we assume that the demand of a customer cannot be satisfied by more than one second-echelon vehicle. Accordingly, each customer is assigned to a satellite and cannot be served by two vehicles from the same or different satellites. Moreover, the vehicles in the first and second echelon have different capacities and they can only serve in the echelon they are assigned to. There are an unlimited number of vehicles available at the main depot and each opened satellite. However, the number of vehicles used in the first and second echelon should be minimized to reduce costs.

The rest of this paper is organized as follows. Section 2 reviews the relevant literature on the 2E-LRP and open VRP (OVRP). Three mathematical programming formulations of the 2E-OLRP are developed in Section 3. Section 4 introduces a hybrid heuristic algorithm that we developed for solving the 2E-OLRP. Computational results on modified benchmark instances are reported in Section 5. Finally, conclusions and future work are discussed in Section 6.

2. Literature review

Cuda, Guastaroba, and Speranza (2015) published a survey on two echelon routing problems that included location routing, vehicle routing, and truck and trailer problems. Similarly, Prodhon and Prins (2014) and Drexl and Schneider (2015) published recent surveys of the LRP and its variants and identified future directions for this area of research.

The literature on vehicle routing problems (VRPs) can be classified according to at least three aspects: (1) the number of echelons in the transportation network, (2) whether a VRP or LRP is considered; and (3) whether routes are open or closed. Below we first discuss papers that consider multiple echelon LRPs with closed routes. Then we review the VRP and LRP studies that have considered open routes.

The location and routing decisions are interrelated and the benefit of considering both decisions in designing distribution systems has been shown in the literature (Salhi & Rand, 1989). Contrary to the classical LRP, the 2E-LRP has only been studied by a few researchers. Jacobsen and Madsen (1980) and Madsen (1983) are the classical papers that first considered the existence of multiple echelons in a location routing problem. They proposed heuristics and compared their performance for designing a newspaper distribution network. Lin and Lei (2009) considered three-echelon distribution systems consisting of distribution centers (DCs), big clients, and small retailers. They proposed a mathematical model and a hybrid genetic algorithm embedded with a routing heuristic to find near optimal solutions in terms of the location and number of DCs and routing in each echelon. They tested the performance of their heuristic method by comparing their results with exact solutions of small problem instances that were solved optimally. Finally, they designed a finished goods distribution system for a Taiwan label-stock manufacturer. Through the case study, they concluded that the inclusion of big clients in the first-level routing in the analysis leads to a better network design in terms of total logistics costs.

Boccia, Crainic, Sforza, and Sterle (2010) proposed a tabu search (TS) heuristic which efficiently combines the following sub-problems: the location and the number of facilities in each echelon, the size of two different vehicle fleets, and the related routes in each echelon. They reported results on small, medium, and large problem instances. Crainic, Sforza, and Sterle (2011) proposed three mixed integer programming formulations for the 2E-LRP; three-index, two-index, and single-index formulations. They evaluated these mathematical models on a large set of examples derived from two-tiered city logistics system settings with various numbers and distributions of potential locations for the two types of facilities.

Nguyen, Prins, and Prodhon (2012b) proposed four constructive heuristics and a hybrid metaheuristic called the greedy randomized adaptive search procedure (GRASP) combined with a learning process (LP) and path relinking (PR). Three greedy randomized heuristics were used to generate trial solutions for the GRASP and learning process, and two variable neighborhood descent (VND) procedures were implemented to improve them. They showed that applying LP and PR improves the performance of their metaheuristic on the classical LRP and 2E-LRP instances. Nguyen, Prins, and Prodhon (2012a) proposed a multi-start iterated local search (MS-ILS) for the 2E-LRP. For generating initial solutions, they used three greedy randomized heuristics based on (a) the Clarke and Wright algorithm, (b) the nearest neighbor heuristic for the TSP, and (c) an insertion heuristic that constructs second-level routes one by one. The ILS run changes between two solution spaces: (i) 2E-LRP solutions and (ii) traveling salesman (TSP) tours covering the main depot and the customers. When a known solution (stored in a tabu list) is revisited, the number of iterations in each run is reduced. Also, they strengthened the MS-ILS algorithm by a path-relinking procedure (PR) which was used internally for intensification and/or post-optimization. On two sets of 2E-LRP instances, they showed that the MS-ILS, on average, outperforms two GRASP algorithms. Also, on capacitated location routing problem (CLRP) instances, their algorithm is more efficient than all algorithms in the literature except the LRGTS algorithm by Prins, Prodhon, Soriano, Ruiz, and Wolfler Calvo (2007).

Schwengerer, Pirkwieser, and Raidl (2012) presented a variable neighborhood search (VNS) algorithm for the 2E-LRP which is an extension of a previous efficient VNS for the LRP. Their algorithm uses seven different basic neighborhood structures parameterized with different perturbation sizes which leads to a total of 21 specific neighborhood structures. They also incorporated the idea of two consecutive local search methods that consider only recently changed solution parts. Their algorithm is efficient in terms of time and quality of solutions compared to the existing results. In Contardo, Hemmelmayr, and Crainic (2012) two algorithms are proposed to deal with the 2E-CLRP. The first one uses a branch-and-cut method based on a new two-index vehicle flow formulation which is strengthened with several families of valid inequalities. An adaptive large-neighborhood search (ALNS) meta-heuristic is also proposed to quickly find good solutions. They show that ALNS outperforms existing heuristics on sets of instances from the literature. Moreover, their branch-and-cut method provides