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A metaheuristic approach to the reliable location routing problem under disruptions

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ABSTRACT

This paper examines a reliable capacitated location–routing problem in which depots are randomly disrupted. Customers whose depots fail must be reinserted into the routes of surviving depots. We present a scenario-based mixed-integer programming model to optimize depot location, outbound delivery routing, and backup plans. We design a metaheuristic algorithm that is based on a maximum-likelihood sampling method, route-reallocation improvement, two-stage neighborhood search and simulated annealing. Numerical tests show that the heuristic is able to generate results that would keep operating costs and failure costs well balanced. Managerial insights on scenario identification, facility deployment and model simplification are drawn.

1. Introduction

The design of a supply chain network is an important issue in today's global competitive environment because of the significant contribution of transportation costs to the overall profit of a company. Most supply chain design models have treated the world as if it was known with certainty. For instance, classical location models such as the p-median problem and the uncapacitated/capacitated facility location problem (UFLP/CFLP), implicitly assume that the chosen facilities, once constructed, will always operate as planned. In reality, however, uncertainties broadly exist. Facilities may face disruptions (e.g., due to natural disasters, labor action, or terrorist attacks) from time to time. Such failures (or disruptions) may result in excessive transportation costs as customers previously served by these failed facilities must now be served by more distant ones.

With respect to uncertainty in supply chain models, Snyder (2003) defined two types of uncertainty: demand-side uncertainty and supply-side uncertainty. The former is usually reflected in demands, costs, lead times, or other aspects involving the distribution of goods to customers, while the latter is often manifest as the availability of plants, distribution centers (DCs), supply capacity, or other facilities required to produce and distribute the product. This paper will focus on supply-side uncertainty, i.e., the existing facilities are subject to unexpected failures. In the context of supply chain design, according to Snyder (2003), a reliable system is one that can perform well even when parts of the system have failed. This ability is often called "reliability" (Snyder and Daskin, 2005).

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Facility location and vehicle routing are two crucial issues associated with network design. Minimizing logistics costs by identifying the optimal facility deployment is usually a strategic decision. The vehicle routing problem (VRP) can be viewed as a tactical or operational decision (Escobar et al., 2013) because deliveries are scheduled on daily/weekly basis. Traditionally, these two decisions have been addressed separately because of their high complexity and difficulty. Salhi and Rand (1989) argued that making these two types of decisions independently might lead to highly suboptimal planning results. In fact, the idea of integrating facility location and vehicle routing under the "location–routing problem" (LRP) dates back nearly fifty years. With regard to uncertainty, most researchers (e.g., Albareda-Sambola et al., 2007; Zarandi et al., 2011, 2013; Zare Mehrjerdi and Nadizadeh, 2013; Ghaffari-Nasab et al., 2013) have considered demand-side uncertainty, i.e., uncertainty in customer demands/presence, or travel time.

This paper studies a version of the LRP in which existing facilities are subject to probabilistic disruption risks. This problem is called the reliable location routing problem (RLRP) (Xie and Ouyang, 2014). In the RLRP, all facilities are capacitated, each of them may fail with a probability (which is known *a priori*), and multiple facilities may fail simultaneously, which is the most significant difference compared with the LRP. A fleet of vehicles can be dispatched from any surviving facilities to serve customers. As in most reliable facility location problems (RFLPs) (Snyder and Daskin, 2005; Cui et al., 2010; Aboolian et al., 2012) and reliable location inventory problems (RLIPs) (Chen et al., 2011; Qi, 2013), the RLRP assumes that customer demands and traffic conditions are deterministic and constant throughout the decision process, and when a facility fails, it is completely unavailable to serve customers. When a facility disruption occurs, the affected customers are either serviced by other facilities or lost. The objective is to determine the facility locations, outbound delivery routing and backup emergency plans under disruptions, so as to minimize the expected total cost, including facility location costs, routing costs and service loss penalties.

The RLRP is a two-stage stochastic problem: strategic location decisions must be made before any failure occurs, while routing decisions (assignment of customers to surviving facilities, delivery tours) are made in the future after the uncertainty has been resolved. Like previous reliable facility location models (e.g., Snyder and Daskin, 2005; Chen et al., 2011; Xie and Ouyang, 2014), we assume that new facilities are not allowed to open in this stage. When some facilities are disrupted, the customers originally assigned to them must be reinserted into the current routes of other operational facilities to hedge against failures, so that rerouting is required. Under an emergency situation in which the surviving facilities are known, a Multi-Depot Vehicle Routing Problem (MDVRP) can then be solved to generate backup plans.

In this work, uncertainty is modeled by a set of discrete scenarios. Each scenario, with a specific probability of occurrence, specifies a subset of facilities that become non-operational or disrupted. The affected customers are then served by an emergency plan. Obviously, allowing more surviving facilities to cover customers that were once serviced by a disrupted facility will increase the flexibility of operation. We first model the RLRP as a scenario-based integer program, and then design a hybrid metaheuristic. The solution approach combines, in a nested schema, a maximum-likelihood scenario sampling procedure, a solution improvement procedure based on route allocation, various two-stage neighborhood exploration strategies and a simulated annealing (SA) framework. Numerical studies are conducted, and some managerial insights are drawn (e.g., substantial improvements in reliability can be attained with lower increases in operational cost).

The main contributions of this paper are as follows: First, we develop a mixed integer program (MIP) for the two-stage stochastic location routing problem considering facility disruptions. Second, we formulate a route-allocation subproblem and solve it via Lagrangian relaxation to simultaneously optimize location and allocation decisions. Third, we develop an efficient metaheuristic to solve the problem and show the advantage of the RLRP solutions compared with other solutions from classic models (i.e., CFLP, RFLP, the capacitated LRP (CLRP)).

The rest of this paper is organized as follows. Section 2 reviews the related literature. Section 3 proposes a scenario-based integer programming model for the RLRP, while Section 4 presents a hybrid metaheuristic approach. Section 5 conducts computational study to test the presented approach and draw managerial insights. Section 6 concludes the paper and briefly discusses future research directions.

2. Literature review

In this section, we briefly review studies that are related to this paper, including methodologies for solving the deterministic LRP, models for the LRP with demand-side uncertain data, reliability issues with respect to supply chain models and location–routing/inventory models arising in humanitarian logistics. Various LRPs have been studied over recent years; comprehensive reviews are contained in Min et al. (1998), Nagy and Salhi (2007), Prodhon and Prins (2014) and Drexl and Schneider (2015). Most authors have addressed the LRP with regard to capacity constraints on both depots and vehicles, i.e., the CLRP, which is also the assumption in this paper.

Earlier research focused on the deterministic CLRP. In a deterministic planning situation, information about the problem is fully known in advance. The CLRP assumes that facilities are always available. With respect to methodologies, some authors developed lower bounds. Barreto et al. (2007) found a lower bound based on a cutting plane method. Exact methods for the CLRP are very recent. Belenguer et al. (2011) strengthened the CLRP using valid inequalities and proposed a branch-and-cut algorithm based on a zero-one linear model. Some exact methods exploit set-partitioning formulations. Akca et al. (2009) described a branch-and-price approach. Contardo et al. (2013) used a branch-and-cut-and-price algorithm and introduced five new valid inequalities. We note that the CLRP is an NP-hard problem (Nagy and Salhi, 2007); all of these methods