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An incremental approach using local-search heuristic for inventory routing problem in industrial gases

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ABSTRACT

In this paper we solve the inventory routing problem (IRP) occurring in industrial gas distribution where liquefied industrial gases are distributed to customers that have cryogenic tanks to store the gases on-site. We consider a multi-period inventory routing problem with multiple products assuming deterministic demand rates and the proposed model is formulated as a linear mixed-integer program. We propose an incremental approach based on decomposing the set of customers in the original problem into sub-problems. The smallest sub-problem consists of the customer that needs to be delivered most urgently along with a set of its neighbors. We solve each sub-problem with the number of customers growing successively by providing the solution of the previously solved sub-problem as an input. Each sub-problem is then solved with a randomized local-search heuristic method. We also propose an objective function that drives the local-search heuristics toward a long-term optimal solution. The main purpose of this paper is to develop a solution methodology appropriate for large-scale real-life problem instances particularly in industrial gas distribution.

1. Introduction

The inventory routing problem (IRP) is a challenging problem that arises in various real-life distribution systems. It involves managing inventory and vehicle routing simultaneously where the vendor is responsible for the replenishment of a set of geographically dispersed customers (Campbell et al., 1998). These customers have demands for different products spread over time, and are entitled to keep local inventory. Deliveries are usually made using a fleet of capacitated trucks. The usual vehicle routing problem (VRP) is a much less complex problem than the IRP problem (Bertazzi and Speranza, 2012). In the VRP, routing decisions are made to fulfill, by the end of the day, fixed orders placed by the customers. In the IRP, the routing decisions are dictated by the anticipated inventory behavior of the customers, which is itself driven by their daily demand patterns. Given the customers' inventory data and information on the customers' demands, the logistics analyst must consequently make following important decisions over a given planning horizon:

- When to visit each customer during the planning horizon
- How much to deliver to each customer on each visit
- How to combine customer visits into vehicle routes

In an industrial setting, the IRP can be applied to various distribution systems. Traditionally, researchers and practitioners have focused on applications to the maritime, automotive and supermarket industries, for example (Campbell and Savelsbergh, 2004). In this paper, we focus on the IRP problem in industrial bulk gas distribution for a finite-horizon scenario (e.g., 2 weeks). We assume that the customer's demand is known (deterministic) and is also dynamic. In industrial gas distribution, liquefied gases [e.g., oxygen (O_2), nitrogen (N_2), argon (Ar), carbon dioxide (CO_2), and hydrogen (H_2)] are transported from production plants to cryogenic storage tanks placed at customer sites using cryogenic trailers. This is primarily done through a VMI system (You et al., 2011). In a VMI system, it is the vendor's responsibility to prevent customer stock-out of the product and avoid penalty consequences. However, there are generally a relatively small percentage of customers that call the vendor to place their orders (non-VMI/call-in customers). There are some features of IRP for bulk gas distribution which are unique compared to the classical IRP model. The IRP for bulk gas distribution includes inventory level constraints for both suppliers and customers. Unlike typical IRP systems, a cryogenic trailer cannot deliver different products in a single delivery. There can be other

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specific routing constraints (e.g., some customers should always be delivered first in a trip).

In this paper, we refer to the combination of a driver, a tractor and a cryogenic trailer as a vehicle. The liquefied gas products are stored at the vendor's production plants and also at the customer sites in cryogenic tanks of various sizes. An industrial gas bulk distribution schedule is generally executed for a smaller time horizon (e.g., 1–3 days), but the planning is done over a longer horizon (e.g., 7–14 days). This study assumes that the scheduling problem is solved daily at a given time with the schedule actually implemented only for the first day of the horizon. Each schedule consists of a set of shifts. A shift is defined as a sequence of activities performed by a single driver within a single working period. In a VMI context with some call-in orders, there are three primary objectives:

- Satisfy all call-in orders
- Maintain all VMI customers above safety levels
- Minimize logistics ratio which is defined as the overall cost per unit product delivered

The uncertainty in scheduling generally arises from many factors including unanticipated customer orders, un-forecasted changes in VMI customer demand, lack of product availability from default sources, driver unavailability, and tractor/trailer unavailability due to breakdowns or unplanned maintenance. In this paper, uncertainty in the parameters is not considered.

This paper assumes that the vendor has telemetry access to monitor storage tank levels at VMI customer sites. Based on the tank levels, historical consumption rates are calculated which are used to forecast the demand during the planning horizon. In practice, logistics analysts plan the deliveries to customers for the scheduling horizon. Scheduling horizon is the period for which the planned deliveries are executed. The objective of this paper is to solve the industrial gas IRP problem within a reasonable time-frame (less than half-an hour) and generate a useful delivery schedule.

2. Literature review

Federgruen and Simchi-Levi (1995) provides the motivations for the IRP and develop a framework that distinguishes two variants of the IRP: the single period model, with stochastic demand, and the infinite horizon model, with deterministic demand rate. Two articles, namely Federgruen and Zipkin (1984) and Anily and Federgruen (1990) illustrate these classifications. Though this classification gives an initial overview of the different aspects of the IRP, it overlooks several approaches that do not fit this description, such as single period models with deterministic demand, multi-period models, and infinite horizon models with stochastic demand. A second attempt to classify the IRP can be found in Baita et al. (1998). In this review paper, IRP is defined as a class of problems having the following aspects in common: routing, inventory, and dynamic behavior (repeated decisions have to be made). Within this class of problems, a classification framework is proposed that takes into account all of the characteristics of the different approaches encountered in the literature: topology of the problem, number of items considered, type of demand considered, type of decision to be taken, constraints considered, objectives sought, costs considered and solution approach proposed.

In this paper, we consider a multi-period finite horizon model with deterministic demand specific to industrial gases distribution. We highlight few important papers that deal with a similar problem. Aghezzaf et al. (2006), Archetti et al. (2007), Campbell and Savelsbergh (2004), Chien et al. (1989), Yu et al. (2008), and Benoist et al. (2011) all study a multi-period IRP where the decisions are carried out over a finite horizon. We should note that most of the studies dealing with the infinite horizon problem use a distribution policy that is similar to the fixed partition policy (first introduced in Anily and Federgruen, 1993), direct deliveries, order-up-to level policy and zero-inventory ordering (Bertazzi et al., 2002; Chan et al., 1998). Refer to Coelho et al. (2014) for the history of IRP and a recent detailed review of different exact and heuristic approaches which can be used to solve wide variety of IRP models.

To solve the IRP, most published research has focused on heuristic solution approaches due to the problem's NP-hard complexity. Frequently, the integrated problem is decomposed into sub-problems (Campbell and Savelsbergh, 2004) which are solved by approximate or exact methods (i.e. Branch and Cut, Column Generation). In some cases, heuristic methods are applied to the sub-problems in order to identify upper and lower bounds. In some IRP papers, integrated and iterative approaches are provided and the effectiveness of integrating routing and inventory decisions in the models is evaluated. Others have proposed heuristic methods to be compared with approaches used in industry (Campbell et al., 2002; Dror and Ball, 1987).

We next provide a list of more recent papers using heuristic approaches to solve IRP. Liu and Lee (2011) solve the IRP with time windows using tabu search to improve a given initial solution on the basis of the average supply chain cost consisting of transportation cost, time window violation penalty cost and inventory cost. Archetti et al. (2010) combine tabu search with mixed integer programming models to solve an IRP with a multi-period horizon where a supplier uses a single vehicle to serve a set of customers having limited capacity to hold inventory. Abdelmaguid et al. (2009) develop constructive and improvement heuristics to obtain an approximate solution for the IRP with backlogging. This considers a case having a depot with an infinite supply of a single product satisfying deterministic demand at each customer. Huang and Lin (2010) introduces a modified ant colony optimization for the IRP having multi-item replenishment with uncertain demand. A three-phase heuristic to solve multiple-product IRP is developed by Cordeau et al. (2015). In the first phase, replenishment plans are determined by a Lagrangian-based method, sequencing of the planned deliveries is performed in the second phase, and the third phase incorporates planning and routing decisions into a mixed-integer linear programming model. Moin et al. (2011) address a finite-horizon, multi-period, multi-suppliers, and multi-products IRP problem with a fleet of homogenous vehicles and propose a hybrid genetic algorithm based on the allocation first route second strategy to solve medium and small-sized IRP problems.

More recent research papers that deal with optimal distribution of industrial gases supply-chains are by You et al. (2011), Benoist et al. (2011), Ellis et al. (2014) and Marchetti et al. (2014). You et al. (2011) focus on strategic decisions with long-term planning horizon using decomposition and continuous approximation approaches. Similarly, Ellis et al. (2014) optimize the strategic-level decision of allocating bulk gas tanks to customer sites. Marchetti et al. (2014) assess the benefits of optimal coordination of production and distribution in industrial gas supply-chains. Benoist et al. (2011) propose a method to solve a real-life IRP for operational scheduling using a randomized local-search heuristic for short-term planning horizon. This method uses a novel surrogate objective function based on long-term lower bounds and report savings exceeding 20% on average compared to solutions built by expert logistics analysts. This method applies a greedy algorithm to generate an initial solution which is then improved upon by the local-search heuristic. In this paper, we apply the same local-search methodology to generate optimal solutions without using greedy algorithm for initial solutions. The local-search heuristic approach is interesting to solve real-life IRP scheduling decisions due to its