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Two-layer simulated annealing and tabu search heuristics for a vehicle routing problem with cross docks and split deliveries

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ABSTRACT

Cross docking plays an increasingly important role in improving the efficiency of large-scale distribution networks. Unlike traditional warehouses, cross docks hold little or no inventory. Instead, goods from incoming trucks are unloaded and immediately transferred through the cross dock to outgoing trucks. Thus, cross docks serve to reduce inventory holding costs and shorten lead times from suppliers to retailers. However, to fully realize these benefits, trucks must be effectively coordinated at each cross dock. Such coordination brings a challenging extension to vehicle routing problems. In this paper a new vehicle routing problem with cross docks and split deliveries is proposed. A mixed-integer linear programming formulation is established for this problem, along with solution methodologies combining a constructive heuristic with two-layer simulated annealing and tabu search. The constructive heuristic creates a solution which is further improved by two-layer variants of simulated annealing or tabu search. The first layer optimizes the allocation of trucks to cross docks while the second layer optimizes the visitation order to suppliers and retailers for trucks assigned to each cross dock. Experimental results demonstrate that the proposed approach effectively solves large-size problems within a reasonable computational time.

1. Introduction

Logistics-related activities are significant cost drivers for many industries. For example, the logistics and transportation industry in the United States spent approximately $1.33 trillion in 2012, or about 8.5% of GDP (Gue, 2014). In 2002, transportation activities accounted for 63% of total logistics costs in the U.S., with inventory-carrying costs accounting for an additional 33% (MacroSys Research & Technology, 2005). That same year, nearly 60% of the weight, and two-thirds of the value, of shipments were hauled by trucks (Federal Highway Administration, 2015). Today, it is estimated that nearly 70% of all freight tonnage (9.2 billion tons annually) in the U.S. is moved by trucks, requiring nearly 3 million heavy-duty trucks, over 3 million drivers, and over 37 billion gallons of fuel (American Trucking Associations). Given the heavy reliance on trucking, the costs of which are significantly affected by fluctuating oil prices and increasing competition, industries have been forced to implement novel cost-reduction strategies.

One such strategy involves the use of distribution centers to facilitate the consolidation of goods from a network of suppliers to be shipped to a variety of retailers. Distribution centers may be classified as being either inventory storage points or inventory coordination points. The former is descriptive of a traditional warehouse, while the latter is descriptive of a cross dock (Kreng & Chen, 2008). A key distinction between the two is that cross docks typically hold inventory for no more than 24 h. The cross docking strategy promises great potential to reduce transportation costs and delivery times without increasing inventory (Sung & Song, 2003). In fact, cross docking has been credited as a key driver of Wal-Mart's superior logistics management (Hammer, 2004). Home Depot reports that its adoption of cross docking strategies have reduced overall inventory by $1 billion. In addition to the cost savings, stock-outs were reported to have been cut in half (Maloney, 2009).

In a cross dock operation, incoming trucks arrive at the receiving doors, where pallets of goods are unloaded. Each incoming truck may have goods to be loaded on multiple trucks for delivery.

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The incoming pallets are sorted according to their destination and moved to a staging area associated with a particular outgoing (initially empty) truck. Goods in staging areas are then loaded onto the outgoing trucks for delivery. Unlike traditional warehouses, in which inventory may be held for an extended period, cross docks emphasize vehicle coordination and consolidation activities. When properly implemented within a distribution network, cross docks promise to reduce inventory levels and delivery lead times.

Motivated by the benefits of cross docking, many studies have focused on the cross dock itself, such as cross dock layout design (Bartholdi & Gue, 2000, 2004), analysis of retailer inventory levels when using cross docks (Waller, Cassady, & Ozment, 2006), and scheduling of trucks at cross dock doors (Boysen, Briskorn, & Tschöke, 2013; Boysen & Fliedner, 2010; Nassief, Contreras, & As'ad, 2014). Many studies have been conducted separately on the vehicle routing problem (VRP) and cross docking. Over the last decade there has been an increased focus on research integrating VRPs and cross docks. This paper examines such a problem which additionally features the practical issues of delivery time windows, heterogeneous vehicles, split deliveries, and storage space limitations within cross docks.

1.1. Problem overview

The problem studied in this paper involves multiple suppliers (manufacturers), consumers (retailers), and cross docks. A simple example of such cross docking network is shown in Fig. 1. Suppliers, retailers, and cross docks are assumed to have time windows in which pickup/delivery service may be provided. Each retailer has a known demand for goods from each supplier. Goods must be delivered from suppliers to retailers through one or more cross docks using a fleet of heterogeneous vehicles of potentially-differing capacities. The vehicles may be routed in a truckload (TL) or a less-than-truckload (LTL) operation. LTL operations occur when the loaded capacity of the vehicle for a particular route is less than the capacity of the vehicle. While LTL operations are beneficial for rapid response to customer requests, they lead to increased costs due to underutilized trucks. To reduce the occurrence of LTL operations (i.e., to maximize vehicle utilization), split deliveries, in which multiple vehicles may deliver goods at separate times for a retailer, are allowed in this system.

Within each cross dock, goods arriving on multiple inbound trucks are sorted and consolidated onto multiple outbound trucks. The majority of these goods are transferred directly to the loading area, where they may be re-sorted in accordance with the delivery sequence for each outgoing truck. Some arriving goods that cannot be transferred directly to the appropriate outgoing truck may be stored in the temporary inventory area.

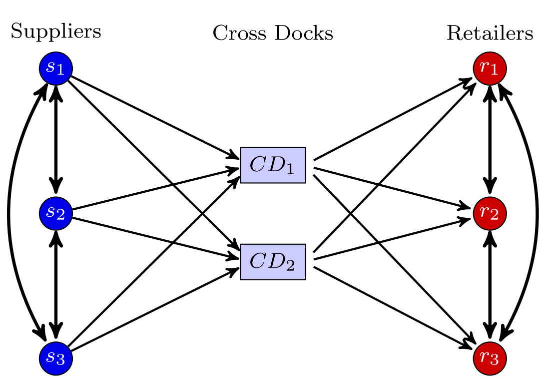

Fig. 1. A representative cross dock network.

The problem is to select the proper vehicles from a fleet of candidate vehicles and determine the route of each selected vehicle to pickup goods from suppliers, transfer these goods to other vehicles via cross docks, and deliver goods to customers. Meanwhile, the quantity of goods loaded at suppliers and delivered to retailers on each vehicle must be determined. The optimization objective is to minimize the total cost under the condition of meeting all customer demands. A detailed problem description is provided in Section 3.

The main contributions of this paper include: (1) a new vehicle routing problem with cross docks and split deliveries is proposed, which considers more practical issues; (2) a mixed-integer linear programming model is established for this problem; and (3) a methodology combining constructive heuristics with simulated annealing or tabu search heuristics is proposed to address this problem.

The remainder of this paper is organized as follows. A review of related literature is presented in Section 2. A formal definition of the problem, as well as its mathematical formulation, is given in Section 3. Section 4 describes the proposed solution approach in detail, followed by a numerical analysis regarding the effectiveness of the solution approach in Section 5. Finally, a summary and opportunities for future research are outlined in Section 6.

2. Related literature

We restrict our focus to research related to the intersection of cross docking and vehicle routing. The interested reader is referred to several recent reviews that address a broader scope of cross docking concepts. For example, Boysen and Fliedner (2010) reviewed truck scheduling at cross docks and proposed a classification scheme based on door environment, operational characteristics, and objectives. Future research challenges are also outlined by Stephan and Boysen (2011), while guidelines for the successful use and implementation of cross docks were discussed by Van Belle, Valckenaers, and Cattrysse (2012). More recently, Buijs, Vis, and Carlo (2014) identified 24 individual decision problems to cover the scope of cross docking design and coordination. Among these problems is the class of vehicle routing problems with cross docks (VRPCD).

Table 1 presents a summary of the literature on vehicle routing in a cross docking environment, and also contrasts the problems in the existing literatures with our problem. The "product types" column describes four classifications: identical (all suppliers provide the same product), suppliers (customer demands are per supplier), multiple (there are numerous products, some of which may be offered by multiple suppliers), and 1:1 (each supplier can serve only one customer, and each customer has demand from a single supplier). The "# of CD" column identifies the number of cross docks. Vehicles are classified as heterogeneous if they differ according to capacity, travel speed, or any other distinguishing feature. The "direct ship" column identifies whether products may be shipped directly from a supplier to a retailer/customer (bypassing a cross dock). The "R-R/S-S" column indicates whether vehicle routes between suppliers or between retailers are permissible. Split deliveries occur when multiple vehicles deliver goods to a single customer, perhaps at different times. The "TW" (time window) column indicates whether pickups and deliveries must occur within some pre-defined time interval. Finally, the last column indicates whether temporary inventory storage is allowable at a cross dock and is explicitly tracked (e.g., with space or time restrictions).

Sung and Song (2003) developed an integrated service network design problem that features multiple cross docks, multiple origin and destination nodes, and two types of vehicles that differ only by