Computers & Operations Research 40 (2013) 2340–2356

Contents lists available at SciVerse ScienceDirect

Computers & Operations Research

journal homepage: www.elsevier.com/locate/caor

Computational comparison of two formulations for dynamic supply chain reconfiguration with capacity expansion and contraction

Wilbert Wilhelm*, Xue Han, Chaehwa Lee

Department of Industrial and Systems Engineering, Texas A&M University, TAMUS 3131, College Station, TX 77843-3131, USA

ARTICLE INFO

Available online 27 April 2013

Keywords:
Supply chain design
Dynamic supply chain reconfiguration (DSCR)
Capacity expansion
Capacity contraction
Mixed integer programming (MIP)

ABSTRACT

The strategic dynamic supply chain reconfiguration (DSCR) problem is to prescribe the location and capacity of each facility, select links used for transportation, and plan material flows through the supply chain, including production, inventory, backorder, and outsourcing levels. The objective is to minimize total cost. The network must be dynamically *reconfigured* (i.e., by opening facilities, expanding and/or contracting their capacities, and closing facilities) over time to accommodate changing trends in demand and/or costs. The problem involves a multi-period, multi-product, multi-echelon supply chain. Research objectives of this paper are a traditional formulation and a network-based model of the DSCR problem; tests to promote intuitive interpretation of our models; tests to identify computational characteristics of each model to determine if one offers superior solvability; and tests to identify sensitivity of run time relative to primary parameters.

1. Introduction

A supply chain must be dynamically *reconfigured* (i.e., by opening facilities, expanding and/or contracting their capacities, and closing facilities) over time to cope with changes in demand and/or cost structures as the business environment evolves. Demand for products in each market and costs to produce them at each plant vary as economic factors change over time. For example, an economic downturn or a period of rapid growth may give rise to such changes and force an enterprise to reconfigure its supply chain to meet customer demands at the lowest possible cost [1]. Another example of a phenomenon that gives rise to such changes is the product life cycle: demand increases after introduction, grows rapidly, plateaus, and then decreases as the end of the life cycle approaches.

The dynamic supply chain reconfiguration (DSCR) problem is to prescribe facility opening, capacity expansion and contraction, and facility closing at each potential location in a multi-period, multi-product, and multi-echelon supply chain. This strategic problem involves a planning horizon of some 6–10 years. DSCR models are needed to provide decision support for management in dealing with changing business conditions in the competitive modern business environment. The objectives of this research are

- a traditional formulation and a network-based model of the DSCR problem,
- tests under different demand scenarios to promote an intuitive interpretation of our models,
- tests that identify the computational characteristics of our models to assess solvability, and
- tests to identify sensitivity of run time relative to primary parameters.

To achieve the first objective, this paper presents a traditional mixed integer program (MIP) and then proposes an alternative model that relates binary decision variables according to a network structure.

Even though the dynamic facility location problem with facility openings and closings has been studied for some time, there has not been adequate attention to cases that involve capacity expansion and contraction over the planning horizon. Furthermore, little research has been directed to dynamic facility location within a multi-period, multi-product, multi-echelon supply chain network. No prior work has studied the solvability of different model forms.

Our DSCR models prescribe material flow through a four-echelon supply chain: suppliers, plants, distribution centers (DCs), and customer zones (CZs). Each echelon performs a unique function so that each product must be "processed" in each. Each viable transportation link allows shipment from a facility in one echelon to another in the next echelon; no links connect facilities within the same echelon. A viable transportation link is established between a pair of operating facilities and any product can be transported on it. Thus, the problem deals with a dynamic, multi-period, multi-product, multi-echelon supply chain network through which products are delivered to satisfy demands, which occur only in CZs.

---

* Corresponding author. Tel.: +1 979 845 5493; fax: +1 979 847 9005.
E-mail addresses: wilhelm@tamu.edu (W. Wilhelm), amethystlulu@neo.tamu.edu (X. Han), chaehwalee@tamu.edu (C. Lee).

0305-0548/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.cor.2013.04.011

We model inventory, backorders, and outsourcing in each time period over the planning horizon because they allow peak demands to be satisfied and are thus essential to customer service. Previous studies have addressed these features in strategic planning [1–6]. Of 60 papers reviewed by [7], 33 include inventory planning in facility location and supply chain management models.

Following [1], which studied dynamic facility location with inventory planning, we consider two cases for contraction and closure costs. In Case 1, it can be profitable for a contractor to close a facility to eliminate unused capacity because the associated cost is negative, indicating that a return can be obtained by selling infrastructure and equipment that is no longer needed. In Case 2, the costs to contract or close are positive, so that unused capacity can be economically eliminated only when doing so is less costly than maintaining it (e.g., heating, cooling, insurance, security and taxes).

Supply chains that are reconfigured abound in industry. After the North American Free Trade Agreement (NAFTA) was signed in 1993, many operations were moved from the U.S. to Mexico. Subsequently, China attracted many of these operations; and, now, because wages have risen in China, some are being moved to lower-cost countries in Asia and some are being on-shored to the U.S. [8]. For over a hundred years, the textile industry has moved from one country to another around the world, seeking low cost labor [9]. The current paper deals with structures that underlie both domestic and international supply chains and need only be augmented with international financial issues (e.g., border crossing fees, tariffs, local content rules, and transfer prices) for application to global supply chains [5]. Domestically, General Motors has recently closed plants in the Midwest and open new ones in the south, while other manufacturers streamline their supply chains [10].

This paper is organized in six sections. Section 2 reviews relevant literature. Section 3 presents our alternative DSCR formulations, addressing the first research objective. Section 4 describes results for two test scenarios that promote intuitive interpretation of model results, accomplishing the second research objective. Section 5 reports our computational evaluation, achieving the third and fourth research objectives. Finally, Section 6 offers conclusions and recommendations for future research.

2. Literature review

The DSCR problem is related to four classical OR problems: facility location, dynamic facility location, supply chain design, and production–distribution network design. The facility location problem involves siting a set of facilities to serve a set of customer demands with the objective of minimizing total distance (or cost) incurred by all transports [4,7]. An extension, the dynamic (multi-period) location problem, has been proposed to meet demands and costs as they change over time [7] and as a basis for building comprehensive supply chain network models [7].

A supply chain network comprises a number of facility types that perform operations ranging from acquiring raw materials, transforming materials into intermediate and finished products, and distributing finished products to customers [6,7]. A specialization of the supply chain design problem is called the production–distribution network design problem [11], which is also a special case of the network design problem in which the network is acyclic.

Due to the wide range of applications and its challenges to solution methods, the dynamic facility location problem with opening and closing has been studied widely since the first work of [12], including both uncapacitated [13–15] and capacitated [16–19] cases. The dynamic supply chain network problem, which includes locating facilities, has been studied by [1,6,15,21] and [23].

The possibility of expanding capacity was considered by [24]. Lowe and Preckel [25] modeled the capacity-contraction case. A few studies [1,21,26,27] considered both capacity expansion and contraction. Daskin et al. [4], Melo et al. [7] and Klose and Drexel [11] provided surveys of the dynamic facility location problem.

In particular, a few papers are closely related to this research. Hinojosa et al. [22] dealt with the multi-period, multi-product, two-echelon, capacitated location problem in which new facilities can be opened and existing facilities closed but did not consider practical features like inventory, capacity expansion and contraction, or a budget limitation. Melo et al. [1] considered the step-wise reallocation of capacities under the assumptions that all existing facilities are operating at the start of the planning horizon; if an existing facility is closed, it cannot be reopened; and when a new facility is opened, it will remain in operation.

Behmardi and Lee [27] studied a dynamic, multi-product, capacitated facility location problem in which each facility can be opened and subsequently closed with no reopening allowed. Extending [22], [6] formulated a model for a dynamic, two-echelon, multi-product, capacitated facility location problem with inventory and outsourcing. Thanh et al. [28] proposed a MIP to design of a multi-product, multi-echelon, production–distribution network, considering the opening, expanding, and closing of facilities as well as supplier selection. Inventories were held only in warehouses, not in plants. Torres-Soto [29] studied the dynamic, capacitated facility location problem, which determines the optimal locations and times for opening facilities when demand and cost parameters are time-varying. This model minimizes costs of transporting and the opening, operating, closing, and reopening of facilities. As in [30], [29] employed binary variables for (re)opening, closing, and operating a facility, but neither allowed for capacity expansion or contraction.

In most models that allow only facility opening and closing [1,6,14,22,27,28], the capacity of a facility cannot be increased or decreased over time. Facilities that are open at the start of the planning horizon can only be contracted or closed and, after closing, must remain closed until the end of planning horizon. Facilities that are not operating at the start of the planning horizon can only be opened and subsequently expanded; but an open facility must remain opened until the end of the planning horizon—it cannot be closed and its capacity cannot be contracted. In particular, this approach does not allow for a facility with excessive capacity to be closed or contracted. Our model fills this gap, allowing capacity expansion and contraction as well as closures.

A number of solution approaches have been proposed: commercial mathematical programming software [1,21,23], branch and bound (B&B) [14,15,20], Benders decomposition [29,31], dynamic programming [18,19,32], Lagrangian relaxation [22,29] and heuristics [13,16,17,26]. As [11] indicated, the computational challenge presented by the dynamic facility location problem increases drastically with the size of the model, reducing the chances to solve large-scale, real-world instances.

3. Model formulation

This section presents our two formulations of DSCR: a traditional MIP, DSCR-T; and a network-based model, DSCR-N. DSCR-T results from traditional logic to relate binary decision variables that prescribe reconfiguration; and DSCR-N utilizes a specialized network to relate binary decision variables to prescribe the same decisions.