



A computational study for common network design in multi-commodity supply chains



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ABSTRACT

In this paper, we study a supply chain network design problem which consists of one external supplier, a set of potential distribution centers, and a set of retailers, each of which is faced with uncertain demands for multiple commodities. The demand of each retailer is fulfilled by a single distribution center for all commodities. The goal is to minimize the system-wide cost including location, transportation, and inventory costs. We propose a general nonlinear integer programming model for the problem and present a cutting plane approach based on polymatroid inequalities to solve the model. Randomly generated instances for two special cases of our model, i.e., the single-sourcing UPL&TAP and the single-sourcing multi-commodity location-inventory model, are provided to test our algorithm. Computational results show that the proposed algorithm can solve moderate-sized problem instances efficiently.

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1. Introduction

Today's enterprises are faced with much more fierce competition than ever before in the context of economic globalization. Integrated supply chain design is becoming increasingly important in strategic enterprise management. It deals primarily with problems such as production planning and control, distribution network design, logistics, and inventory management. These factors together make up the production–distribution process in its entirety, from raw materials to final products. Integrated supply chain design has a direct impact on the effectiveness of business operations. A good supply chain design not only saves logistics and operations costs, but also improves service levels, increases customer satisfaction, and thus increases the competitiveness of an enterprise. Therefore, the problem of how to better design and manage a supply chain has become a very important issue that must be addressed for many business managers.

Integrated supply chain design involves determining optimal distribution center (DC) location, technology selection, distribution network configuration, inventory management, and product delivery. Generally, these decisions can be classified into three levels: the strategic level, the tactical level, and the operational level (cf. Chopra and Meindl [5] and Shen [16]). The strategic level decision making addresses issues such as facility location, technology selection, and network configuration. At the tactical and

operational levels, attention is given to inventory management, logistics planning and management under fixed supply chain topologies. Traditionally, these decisions are usually treated separately in the literature. However, they are closely related to each other, e.g., the strategic location decision can have significant impact on the inventory replenishment and distribution decisions (cf. Shen et al. [16]). In recent years, more and more studies have started to emphasize the integration of these decision-making levels.

Integrated supply chain design is typically very complex and computationally challenging. Most existing integrated supply chain design models study a single-commodity supply chain. In this paper, we study a multi-commodity supply chain design problem with an external supplier, a set of potential distribution centers (DCs), and a set of retailers. Each retailer faces uncertain demands for multiple commodities. Given the demand information (expectation and variance) for each retail outlet and commodity type, the potential DC locations, the location of each retailer, and the DC operating and transportation cost parameters, we want to simultaneously determine: (i) how many DCs to open and where to locate them, (ii) DC-retailer assignment, so that the total system-wide cost of the supply chain network is minimized, including: (i) fixed DC setup cost and DC operating cost, (ii) transportation cost, (iii) inventory replenishment and safety stock cost or technology cost. The existing integrated multi-commodity supply chain design models allow each retailer to source different commodities from different DCs so that they are computationally tractable. This means that the DC-retailer distribution network is designed separately for each commodity, which can often bring

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additional costs in practice (cf. Snyder et al. [25]). In contrast, in this paper, we force each retailer to adopt the single-sourcing strategy, i.e., each retailer can only receive replenishment of all commodities from a single DC. Shen [16] shows that the submodular function minimization subproblem arising from the Lagrangian relaxation solution approach for this problem can be solved using a general purpose submodular function minimization algorithm whose complexity is $O(n^7 \log n)$ (where n represents the number of retailers). Orlin [12] improves this complexity to $O(n^6)$. Given that this subproblem must be solved in each iteration of the Lagrangian relaxation approach, it is unlikely to solve the problem efficiently in this way. In this paper, we combine valid inequalities for the convex lower envelope of a submodular function and the second-order conic reformulation strategies proposed by Atamtürk and Narayanan [1] and Atamtürk [4], respectively, to develop a cutting plane algorithm that works well for the single-sourcing problem studied.

The remainder of the paper is organized as follows. We review the relevant literature on integrated supply chain design as well as the recent development on conic integer programming in Section 2. In Section 3, we present the general model for the single-sourcing multi-commodity supply chain design problem. In Section 4, we outline a cutting plane solution approach based on polymatroid inequalities to solve the problem. Computational results for two integrated supply chain design problems using the proposed algorithm are reported in Section 5. Finally, we conclude the paper in Section 6.

2. Literature review

In this section, we first review the closely related literature on integrated supply chain design models, followed by the recent developments on conic integer programming. There are two main types of integrated supply chain design models in the existing literature, namely, integrated location and multi-echelon inventory network design models and integrated location and single echelon inventory network design models. For a comprehensive review, we refer readers to Melo et al. [11]. Since the problem we study in this paper is rooted in the integrated location and single echelon inventory network design literature, we focus on reviewing the network design models with single echelon inventory management. For supply chain network design models integrating multi-echelon inventory management, we refer to Teo and Shu [27] and Romeijn et al. [14].

Daskin et al. [7] and Shen et al. [15] are among the first to propose a joint location-inventory model which takes into account the complex trade-off between location cost, transportation cost, and DC inventory cost. The problem can be formulated as a nonlinear integer programming model and solved via a Lagrangian relaxation approach or restructured as a set-covering model which can be solved using a column generation algorithm. Both approaches need to solve a pricing subproblem which is a submodular function minimization problem. An $O(n \log n)$ algorithm is proposed for two special cases: the variance of the demand is proportional to the mean at each retailer, or the demand is deterministic. Shu et al. [23] deals with the model with general demand patterns. Shu et al. [18] and Li et al. [10] present a 1.861-approximation greedy and 3-approximation primal-dual algorithm for this NP-hard problem, respectively. Shen and Qi [17] further incorporate a routing cost term into the joint location-inventory model. Sourirajan et al. [26] generalize the joint location-inventory model by considering stochastic lead time for DC replenishment. Ozsen et al. [13] and Shu and Sun [22] study a capacitated version and a two-stage stochastic version of the joint location-inventory model, respectively. All of the aforementioned models assume a single commodity supply chain. Shen [16] and Snyder et al. [25] propose a multi-commodity location-inventory model independently. Our work

is closely related to theirs. Their model is very general since many well-studied problems can be viewed as special cases of their model, e.g., the multi-commodity version of the joint location-inventory models and the Uncapacitated Plant-Location and Technology-Acquisition Problem (UPL&TAP) proposed by Dasci and Verter [6]. In their model, the DC-retailer assignment variable is set to be commodity-dependent, which means each retailer will source different commodities from different DCs. This assumption makes the pricing subproblem decomposable by commodities and thus tractable. As stated in Shen [16], Snyder et al. [25], and Shu et al. [20], this often leads to additional costs and usually single sourcing is forced in practice. In contrast, our model can be viewed as a single-sourcing version of their model by restricting that all commodities are distributed using a common network. This modeling framework is not only valuable in its own right, but also likely to have implications in other areas as well, e.g., bicycle-sharing network design and management (cf. Shu et al. [19]), demand market selection (cf. Shu et al. [24]).

The single-sourcing multi-commodity location-inventory network design model proposed in this paper contains several nonlinear concave cost terms which are not decomposable based on different commodities. It has been demonstrated to be a computationally challenging problem in the literature. Fortunately, with recent advances in the theory of conic integer programming, we can reformulate this nonlinear integer program as a conic mixed-integer program and tackle it using a cutting plane approach based on polymatroid cuts in each iteration. In the rest of this section, we briefly review the recent advancement of conic integer programming. Atamtürk and Narayanan [2] put forward conic mixed-integer rounding inequalities for conic mixed-integer programs, which can significantly reduce the integrality gap of the continuous relaxations of conic mixed-integer programs and thus improve the solvability. Atamtürk and Narayanan [3] give lifting methods for conic mixed-integer programs. Atamtürk et al. [4] use the approach to reformulate several joint location-inventory problems with different types of nonlinearities as conic mixed-integer problems. They show that by adding valid inequalities to the formulations, those problems can be solved directly using standard optimization software packages without need for specialized algorithms. Their new approach provides a more general modeling framework and a much faster solution approach.

3. Notation and formulation

In this section, we introduce the single-sourcing multi-commodity location-inventory network design model which integrates the traditional uncapacitated facility location problem with the inventory management at the facility level for multiple commodities, taking into consideration the economies-of-scale effect. The model can be viewed as the single-sourcing version of the one proposed in Shen [16]. To formulate the model, we use the following notations:

Inputs and parameters:

I	set of retailers
L	set of commodities
J	set of potential DC locations
u_{il}	mean annual demand for commodity $l \in L$ at retailer $i \in I$
σ_{il}^2	variance of daily demand at retailer $i \in I$ for commodity $l \in L$
d_{ij}	per unit cost of shipping commodity $l \in L$ from DC $j \in J$ to retailer $i \in I$

Decision Variables:

x_j	$x_j = 1$ if DC j is open, otherwise $x_j = 0$
y_{ij}	$y_{ij} = 1$ if retailer i is assigned to DC j , otherwise $y_{ij} = 0$

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