Advanced Engineering Informatics 38 (2018) 306–315

Contents lists available at ScienceDirect

Advanced Engineering Informatics

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

Full length article

# Capacitated closed-loop supply chain network design under uncertainty

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ARTICLE INFO

*Keywords:*
Capacitated closed-loop supply chain
Conic quadratic programming
Stochastic programming
Valid inequalities
Tabu search

ABSTRACT

This study optimizes the design of a closed-loop supply chain network, which contains forward and reverse directions and is subject to uncertainty in demands for new & returned products. To address uncertainty in decision-making, we formulate a two-stage stochastic mixed-integer non-linear programming model to determine the distribution center locations and their corresponding capacity, and new & returned product flows in the supply chain network to minimize total design and expected operating costs. We convert our model to a conic quadratic programming model given the complexity of our problem. Then, the conic model is added with certain valid inequalities, such as polymatroid inequalities, and extended with respect to its cover cuts so as to improve computational efficiency. Furthermore, a tabu search algorithm is developed for large-scale problem instances. We also study the impact of inventory weight, transportation weight, and marginal value of time of returned products by the sensitivity analysis. Several computational experiments are conducted to validate the effectiveness of the proposed model and valid inequalities.

## 1. Introduction

Customers' required level of service has increasingly escalated with the improvement in a living standard. In terms of delivery time, the demand for new products is more and more urgent. Companies provide remanufactured products, which are in a looking-new condition and favorable quality to satisfy consumer demand. Many well-known enterprises, such as HP, Xerox, and Kodak, design and operate their supply chains by jointly considering forward and reverse supply chains. These enterprises incorporate their remanufacturing processes into their regular production lines and operations [32]. The closed-loop supply chain (CLSC) has drawn considerable attention from both the academia and the practitioners.

The traditional supply chain management refers to decisions on efficient production and product transportation from suppliers to demand places through one or more distribution centers [33]. By contrast, a CLSC network consists of all necessary components to design, fabricate, sell, and recycle a product [39]. Thus, the CLSC network design should simultaneously consider operations of the forward and the reverse flows. The design of the CLSC network consists of several long-term and short-term decisions; the former determines whether a distribution center should be built and its corresponding capacity, whereas the latter determines the order assignment strategy [14]. The CLSC design and operations management have attracted attention from the academia and industry over the last 20 years [33]. However, the increasing popularity of online shopping has improved the CLSC management to a highly profound level given the rapid development of internet technology. The retail platform of Alibaba Group in China announced that USD 25.3 billion of gross merchandise volume was settled through Alipay on November 11, 2017; this value reflects an increase of 39% compared to 2016. However, its return rate is 62.9% according to unofficial statistics. Thus, a well-designed CLSC network is increasingly significant for online shopping companies, such as Alibaba and Amazon.

This study is motivated by a real-world bottleneck problem encountered during online shopping. Now, with the advance of the internet technology, online shopping has become one of the most active ways for consumers to buy remanufactured products [38]. The supply chain design and operations management is experiencing increasing competitive and regulatory pressures which also lead to new challenges. Hence, supply chain managers are concerned with a novel CLSC network which considers many realistic factors together simultaneously in order to obtain numerous financial benefits. This study investigates a three-tiered supply network that considers capacitated distribution centers, uncertainty demands of new & returned products, risk-pooling strategy to buffer random demands, savings from collocating of a joint

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https://doi.org/10.1016/j.aei.2018.07.007
Received 28 April 2018; Received in revised form 26 June 2018; Accepted 30 July 2018
1474-0346/ 

distribution center, value loss related to inventory and transportation time, and a linear relationship between distribution center capacity and cost simultaneously. We formulate our problem as a two-stage stochastic programming model in which the first stage is responsible for long-term decisions, such as distribution center locations and their corresponding capacities. The second stage corresponds to certain short-term decisions, such as the product transportation assignment optimization under various scenarios. We then convert our original model to a conic quadratic mixed-integer programming (MIP) model and add certain valid inequalities, such as polymatroid inequalities considering the complexity of our problem. Then, we add extended cover cuts to strengthen the model formulation. Moreover, a tabu search algorithm is also suggested to solve the model with large-scale problem instances.

The remainder of this study is organized as follows. Section 2 introduces an overview of related works. Section 3 proposes a non-linear MIP model about the CLSC design and converts it to a conic quadratic MIP model. In addition, certain valid inequalities are developed to improve the computational efficiency. Section 4 details the parts of the tabu search algorithm, which we use for large-scale problem instances. Section 5 discusses the computational experiments under our optimization strategy. Section 6 presents the conclusions drawn from this study.

## 2. Related literature

Numerous studies have been conducted on the CLSC design and optimization given the increasing consumer demand for environmentally friendly products. We review three streams of related literature on supply chain management problems. Readers who are interested in this area can refer to Fleischmann et al. [8], Savaskan et al. [27], Listeş [18], Guide and Van-Wassenhove [13], Zhang et al. [39], and Wu and Kao [37] to obtain a comprehensive overview on supply chain network design and operations management.

The first research stream is related to capacity restrictions in the facility location problems. Facility location decisions significantly influence the strategic design of supply chain networks [20]. Quantitative papers about the facility location problem have been published and the facility location problem has been a well-studied topic within operations research [19]. Facility location problems with minimizing marginal revenue have been studied from various perspectives [4]. In addition, capacity restrictions in the facility location problems are an extension of the original problem and play a critical role [39]. Fischetti et al. [7] use Benders decomposition without separability to conduct computational experiments for solving capacitated facility location problems. Mota et al. [21] present a multi-objective MIP model that integrates several decisions simultaneously, such as capacitated facility locations, supply chain network design, and technology allocation. From a number of related works, an increasing stream of research is aimed at integrating strategic and operational-level decisions in facility location problems. Furthermore, the role of facility locations in supply chain network management is becoming increasingly crucial in a realistic business environment; scholars are also required to develop further comprehensive decision models, which can jointly capture many realistic factors in the supply chain network management [20].

The second topic of related works is concerned with the reverse logistics management issues for remanufactured products. Recently, supply chains with returned products are receiving increased attention in the operations management discipline. Reverse logistics is responsible for taking back returned products and recovering them efficiently and economically [29]. The recovery had a significant economic impact on the industry and society, thereby causing an increase in the type of literature in reverse logistics management issues for remanufactured products [27]. Reverse logistics differs from traditional logistics because the former has unique characteristics, such as coordination requirement of two markets [31]. Fleischmann et al. [9] provide a first review of quantitative models for reverse logistics. Numerous studies related to reverse logistics use game theory to build remanufacturing models. Li et al. [17] present a Stackelberg game model for considering forward and reverse supply chains as an integrated problem. Govindan et al. [12] propose that we should focus on multi-objective problems by using new approaches to realize green, sustainable, and environmental objectives, such as pollution prevention and life-cycle assessment.

The last stream of studies explores the CLSC design and optimization problem. In the modern structure of the supply chain network management, forward and reverse logistics are regarded as an integrated network rather than separate problems [26]. A growing number of firms have realized the importance of CLSC optimization [29]. Sahyouni et al. [43] build three types of uncapacitated CLSC network design models that are aimed at minimizing fixed location and transportation costs. Jabbarzadeh et al. [15] propose a stochastic robust CLSC design and optimization model, which considers lateral transshipment as a reactive strategy to address disruption risks; the authors also develop a Lagrangian relaxation algorithm to solve the problem efficiently. In terms of stochastic problems, Zhen [40] provides both a stochastic programming formulation which can deal with arbitrary probability distributions of ships' operation time deviation, and a robust formulation that is applicable to situations in which limited information about probability distributions is available. Moreover, determining whether uncapacitated or capacitated CLSC network faces the same problem that the sub-problems generated remain intractable and require several cutting-plane methods [39].

In summary, many studies on CLSC optimization problems disregarded the uncertainty of new & returned products on network design. Many CLSC design and optimization problems excluded several realistic factors, such as integrated capacitated distribution center, risk pooling to buffer random demands, and value loss related to inventory and transportation time, although these studies have considered uncertainty problems. Several other factors were frequently ignored, such as the savings from constructing an integrated distribution center, and the relationship between distribution center capacity and cost given the economy of scale. However, these ignored factors are crucial to the real-world CLSC management.

This study conducts a comprehensive investigation of a CLSC network design and optimization problem by considering several realistic factors, such as uncertain scenarios and value loss; these factors are related to inventory and transportation time. In addition, certain valid inequalities are added to strengthen the model formulation. In comparison to the existing literature, the model proposed in this study can provide more reasonable CLSC management plans in real-world application.

## 3. Model formulation and reformulation

We use a relatively simple three-tiered supply chain network as an example to explain the problem background of this study. Fig. 1 illustrates that the underlying strategic and operational setting of our problem consists of three types of facilities, namely, a supplier, several capacitated distribution centers (DCs), and retailers, in this network. The relationship among these facilities flows in two directions, that is, forward and reverse. Specifically, the former is the flow of the retailer's order for a product from the DC which is replenished from the supplier. By contrast, the latter is the flow of returned products from the retailer to the corresponding DC and then back to the supplier for remanufacturing. Clearly, DCs can hold stocks of both new & returned products. Thus, there are three types of DCs in the network: forward DCs which just store new products, reverse DCs which just store returned products, and joint DCs which can store both new & returned products. Since satisfying the needs of overall demand in the designed CLSC network generates a certain cost, the goal of our problem is to minimize the total cost, including the fixed construction cost of each