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A mixed integer nonlinear programming model and heuristic solutions for location, inventory and pricing decisions in a closed loop supply chain

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ABSTRACT

We analyze a network design problem for a closed-loop supply chain that integrates the collection of the used products with the distribution of the new products. We present a mixed integer nonlinear facility location-inventory-pricing model to decide on the optimal locations of the facilities, inventory amounts, prices for new products and incentive values for the collection of right amount of used products in order to maximize the total supply chain profit. We develop heuristics for the solution of this model and analyze the effectiveness of these heuristics and the effects of the parameters on this system through numerical experiments.

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1. Introduction

Closed loop supply chain management (CLSCM) includes all reverse logistics activities as collection, remanufacturing and refurbishing processes in addition to all traditional forward logistics activities from supplier to customer. CLSCM does not only gain increasing attention among society, government and practitioners of operations but also gains the attentions of researchers (see [28] for a review on CLSCM). The growing concern for environment leads integrating environmentally sound solutions into traditional supply chain management in practice. Besides the environmental concerns, recent legislations in many countries force the companies to undertake take-back responsibilities to reduce waste. The governmental concerns create strong legislative incentives on why and how take back activities are organized for different classes of products. WEEE directives in Europe will require all large electronic retailers to take back their old equipment. Companies can also benefit from these used products to decrease their cost of production. End-of-life products that normally go to waste might actually have some remaining value which will reduce consumption of the raw materials and provide cost reduction on waste treatment. In other words, CLSCM is driven by high profitability, increasing number of legislative incentives, and growing awareness for environment. Thus, the companies need to adjust their supply chain to integrate the collection activities of end-of-life products into their traditional distribution channels and design an efficient CLSC.

In this study, considering the inventory, pricing and incentive determination problems in the supply chain, we analyze the network design problem for a closed-loop supply chain that integrates the collection of the used products with the distribution of the new products. In today's world, in which the companies are required to collect a portion of their used products due to legislative issues or cost concerns, they need to integrate their collection network for used products with the distribution network of new products. In this study, we present a mixed integer nonlinear facility location-inventory-pricing model to decide on both the optimal locations of the collection and distribution centers (*CDC*), optimal inventory amounts to be carried at these centers, optimal prices for new products and the values of incentives that need to be offered for the collection of right amount of used products, in order to maximize the total supply chain profit.

Logistics network design is one of the most strategic decisions for CLSCM because opening or closing a facility is very expensive, time consuming and infeasible to change in a short time. Many tactical and operational decisions are limited by this strategic decision because logistic network configuration is directly related to facility locations. Facility location problems have been studied for more than a century, starting from Weber's location problem in 1909 (see Brandeu and Chiu [5] for a review of facility location

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problems). The simplest and one of the most studied location problem is p-median problem which is introduced by Hakimi [12]. This problem analyzes which p facility are to be selected among the potential locations and Mladenovic et al. [22] give a complete survey about metaheuristic approaches applied to p-median problem which is classified as NP-hard. Another type of the facility location models, which is more in line with our study, considers fixed facility location costs, therefore number of facilities to be established becomes an important decision. This problem is known as uncapacitated facility location problem (UFLP) and is extensively studied in literature. Revelle et al. [23] survey a number of important problems in facility location including UFLP. Moreover, an extensive study can be reached in Mirchandani and Francis's book [21].

Collecting the right amount of products is one of the main concerns in a CLSCM and there are two main factors that effect the collection amount; the incentives offered to the customers and the proximity of collection centers to customers. Firstly, some companies offer financial incentives to end users to return their products and as the amount of this incentive increases, more products will be returned. Amount of this incentive plays a major role in the collection activity and it must be critically analyzed to maximize the profitability of the companies. Secondly, accessibility of the collection centers (CC) is another important issue for the customers to return their products. As the number of CCs increase, they will be closer to the customers and more products will be returned, however, opening more CCs might be too costly for the companies. Thus, opening the right number of CCs at the right places is a critical factor for a CLSCM. In addition, in a society, since the end users are generally located at the same place as the new potential buyers for these products, the CCs can be integrated with the companies' traditional distribution centers (DC) to carry out both distribution and collection activities to decrease both facility opening and operating costs. Thus, we aim to determine the best locations for these collection and distribution centers (CDC) in order to maximize the total supply chain profit considering both the forward and the backward flow of products.

In addition to the incentives offered to the end users, we also focus on determining the sales price of new products in order to maximize total profit, which will also depend on the locations of the CDCs. In literature, there are only a few studies that consider pricing with facility location decisions and they mainly focus on pricing issue while designing an optimal drop-off facility network. Wojanowski et al. [29] concentrate on the forward supply chain and using continuous modeling approaches, they determine the sales price of the product by focusing on the deposit-refund policy to maximize firm's profit. In this policy, the sales price is known by the customers including the deposit amount which will be paid back when customer takes back the used product at a collection facility. In that model, customers' willingness with regards to purchasing and returning the product is related to a stochastic utility choice model. On the other hand, Aras et al. [1] concentrate on reverse supply chain and try to optimize only return decision of product holders rather than the purchasing decision under deposit-refund requirements. Another difference between these studies arises from their proposed pick-up policies. In Wojanowski et al. [29], customers have to bring their used products to the collection centers, however, Aras et al. [1] develops a pick-up policy with vehicles of limited capacity.

In this study, we also consider the inventory costs of the CDCs since inventory costs also play an important role in the management of these centers. The collected products from the customers should be sent to the manufacturing facility and new products should be brought from the manufacturing facility at certain time intervals. Therefore, the inventory system should be organized and controlled appropriately to provide integrity between the forward and backward flows of the materials. Since we assume a deterministic rate of demand and a deterministic rate of collection, we use the economic order quantity (EOQ) formulation which has been widely used in the network design literature. For example, Camm et al. [6] develop an uncapacitated facility location formulation for Procter and Gamble Company to locate the DCs and assign the selected DC's to customer zones with the objective of minimizing the total cost, composed of material handling costs, inventory costs and transportation costs, while maintaining a certain customer service level. Daskin et al. [8] propose a location inventory model and its solution methodology, considering the locations of DCs with the working inventory and safety stock costs as well as the economies of scale that exist in the transportation costs from suppliers to DCs.

Reverse and closed loop logistics network design problems are widely studied in literature. Louwers et al. [19] study a facility location allocation model for reusing of carpet waste as a case study and analyze its two applications one in Europe and the other in the United States of America. Jayaraman et al. [14] examine the electronic equipment recovery closed loop network design with multi-product capacitated warehouse location MILP to seek the optimal number and location of remanufacturing facilities while minimizing the total costs. Fleischmann [9] emphasizes a continuous network design model using a MILP model for product recovery and develops a heuristic algorithm. Shih [27] develops a MILP model to design the reverse network flow of computers and home appliances in Taiwan. Jayaramann et al. [15] study on a MILP reverse distribution model to minimize the total transportation and fixed costs of opening facilities and develop a heuristic procedure for this problem. Beamon and Fernandes [2] develop a closed loop supply chain model to determine the location and sorting capability of warehouses and collection centers as well as deciding the quantity of flow between the sites. Schultmann et al. [26], Biehl et al. [4], Lu et al. [20], Ko et al. [16] and Lee et al. [17] are some of the other studies related to reverse logistics network design problems. Listes [18], Salema et al. [24] and Inderfurth [13] consider randomness in reverse logistics problems. Aras et al. [1] develop a discrete facility location–allocation model to find the predetermined number of collection centers and the optimal financial incentive values for different return types and propose a heuristic procedure using two nested loops to solve this problem. In a recent study, Salema et al. [25] formulate a multi-period, multi-product network MILP model for the simultaneous design of a Portuguese glass company's forward and reverse networks. Fuente et al. [10] deal with an integrated supply chain management which combines the new processes taken from reverse supply chain into existing processes of forward supply chain.

Different from the literature, we develop a model that considers a closed loop supply chain in which we analyze the location, inventory and pricing decisions simultaneously. We build a MINLP model for this problem, however due to the complexity of the problem, it is not possible to solve this model using commercial solvers such as BARON for even moderately sized problems (when the number of potential facility locations are 20 or higher). Thus, we develop three hybrid metaheuristic algorithms to solve our model for medium or large sized instances. Simulated Annealing (SA), Tabu Search (TS) and Genetic Algorithms (GA), all hybridized with Variable Neighborhood Search (VNS) are compared in terms of both solution quality and computational time. We also present an upper bound for the objective of our problem based on piecewise linear approximation of a part of the nonlinear objective function and compare the results of the heuristics with this upper bound through an extensive computational study. We also use this piecewise linear approximation technique to develop a heuristic for our problem. In the next section, we define our problem and present our model in detail. Then, in Section 3, we describe the solution methods and the heuristics that we develop for this model and then in Section 4, we present our computational studies. Finally in Section 5, we conclude our study.

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