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A closed-loop supply chain management problem: Reformulation and piecewise linearization

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ABSTRACT

Recent environmental considerations as well as advancements in the field of logistics have promoted the integration of the forward and reverse supply chains, in order to increase operational efficiency and support sustainable operations. In light of this, we formulate a mixed integer non-linear program (MINLP) that describes both the forward and reverse flow of a single type of product, through a set of warehouses whose location is determined based on whether they serve as forward, reverse or joint warehouses dealing with products from both directions. The objective of the model is to minimize the total costs, which include fixed location, fixed ordering, inventory holding, transportation as well as re-processing costs, the latter referring to returned products. In order to overcome the non-linearity of the formulation, the respective constraints are linearized, while for the non-linear terms of the objective function a piecewise linearization is proposed. The computational analysis focuses on comparing the results obtained by solving the MINLP in commercial software with the results obtained from implementing the linearization for a different number of adopted segments for the piecewise linearization. In addition, both integrated approaches are compared to the sequential approach, according to which the location, ordering and transportation problems are initially solved, producing an output that is subsequently used as an input to solve the inventory problem. Results demonstrate the benefits of integration as well as the cost savings that can be achieved due to the closed loop consideration of the supply chain. A discussion of these results produces useful insights for supply chain operators.

1. Introduction

Companies are constantly aiming to improve the design of their supply chains amid accelerated growth and fierce competition of contemporary global markets. Conventional supply chain practices are being constantly re-evaluated as companies find ways of increasing the efficiency and accuracy of their operations. One of the traditional practices that is changing in a supply chain is the flow of products, which in no longer only in the forward direction. In order to make use of returned products companies are adopting reverse logistics in addition to forward logistics, forming what is known as a closed-loop supply chain. One of the reasons for this is the growing interest in product recovery and material recycling, which has expanded the scope of traditional supply chains to include final-users, collection centers, de-manufacturers or remanufacturers. This growing interest is also reflected in recent research streams. Alshamsi and Diabat [1] address one reverse logistics network which takes into account the optimal selection of sites, the capacities of inspection centers and remanufacturing facilities. Aside from redesigning the supply chain network, Govindan et al. [2] focus on reviewing the coordination by contracts of the forward and reverse supply chains, and the authors provide the contract classification based on the criteria of transfer payment contractual incentives and inventory risk sharing.

Another traditional approach that is changing is that decisions at different levels of the supply chain are now being considered simultaneously rather than sequentially. With regards to decision making levels, supply chain management can be categorized into strategic, tactical and operational level decisions, depending on the frequency of making them or the time-frame of impact. For example, decisions on the strategic level have a long-term impact of the company; examples include the location of warehouses, which is a decision usually made once or twice over the life of the company. Tactical level decisions occur at the frequency of several times

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per year and include the selection of transportation means as well as inventory policies. Finally, operational level decisions have the shortest-term impact on the company; they may occur on a daily basis and pertain to scheduling or routing plans. While seemingly independent, these decisions are in fact closely related when it comes to selecting the optimal operations for a company. For example, the location of a warehouse can greatly impact the routing between the retailer and the warehouse and vice versa. Therefore, many researchers have started to address this issue by proposing integrated models; Nagy and Salhi [3] discuss problems and models on the integration of location and routing, while Shen and Qi [4] integrate inventory and routing and Shen et al. [5] integrate inventory and location decisions. Other authors such as Hiassat [6]; Ahmadi Javid and Azad [7] showed the benefits of integrating all three location, inventory, and routing. However, these benefits come at the cost of a considerable increase in computational complexity. Other difficulties that arise are related to the non-linear terms and constraints, as highlighted by Diabat [8].

In light of these facts, the current paper proposes an integrated model which takes both warehouse allocation and inventory policy management into consideration under a closed-loop supply chain network. With regard to the problem description, three different types of warehouses are assumed: the forward warehouse which deals with new product distribution, the reverse warehouse which deals with returned products' collection, and the joint warehouse which can simultaneously conduct forward and reverse warehouse functions. The problem is formulated as a mixed integer non-linear program which aims to minimize the overall cost of the system.

This paper is organized as follows: Section 2 provides a literature review regarding the related topics. Section 3 presents the model formulation and development process of the model. After that, the numerical experiment results of the sensitivity analysis are reported. Finally, the last section concludes this paper and provides discussion of problem extensions and future research directions.

2. Literature review

The aim of the current section is to provide an overview of the relevant literature pertaining to models with integrated decision levels, namely integrated facility location and inventory management decisions, as well as closed-loop supply chains. Recently, both topics have attracted the interest of the research community as they reflect the evolution of supply chains to better accommodate the contemporary facts.

In the notable work by Daskin et al. [9] the authors study a location-inventory model on the basis of risk-pooling as proposed by Eppen [10]. The problem is formulated as a mixed integer nonlinear program, and solved for the special case in which the ratio of the variance of demand to the mean of demand is identical for all retailers by proposing a Lagrangian relaxation based approach. Shen et al. [5] implement a different solution approach by presenting a set-covering formulation of the problem and by proposing a column generation approach to solve it. Diabat and Richard [11] propose a model which simultaneously makes decisions pertaining to location and inventory policies on two echelons of the supply chain, the warehouse and the retailers. Instead of building the model as a mixed integer non-linear program which is prevalent when dealing with the location-inventory problem, they formulate it as an integer programming model. In order to solve the problem, two Lagrangian relaxation based algorithms are developed and compared to a conventional branch-and-bound algorithm on randomly generated instances.

The solid works by Daskin et al. [9] and Shen et al. [5] set the way for future studies which extended their scope. Ozsen et al. [12] introduced capacity limits for warehouses and considered demand occurring during lead times. The authors implemented Lagrangian relaxation and reported near optimal solutions within reasonable time. Based on the same model formulation, Diabat et al. [13] develop a genetic algorithm to solve it and prove that optimal or near optimal solutions are easily reached for benchmark test problems. On another note, the focus of Sourirajan et al. [14]; Sourirajan et al. [15] is the operational performance with respect to stochastic lead times and safety stocks. The authors develop both a Lagrangian relaxation and a genetic algorithm to solve the problem. More recently, Diabat et al. [16] formulate the multi-echelon joint inventory-location problem that makes location, order assignment and inventory decisions simultaneously. In order to overcome the added challenge of solving a multi-retailer problem to optimality, the authors decompose the original problem by warehouse and take advantage of the power-of-two inventory policy. Inspired by the same formulation, later work of Diabat et al. [17] focuses on improving the Lagrangian relaxation based heuristic to more efficiently and accurately solve the large-sized instances Diabat [18].

On the other hand, raising environmental awareness has encouraged supply chains to overcome barriers for sustainable practices, as studied by Al Zaabi et al. [19] and Govindan et al. [2]. In light of this, several topics that aim to enhance the green aspect of supply chains have emerged. These mainly include carbon reduction schemes and product recovery through closed loop supply chains. With respect to carbon reduction, notable works include those of Abdallah et al. [20], Kannan et al. [21], Diabat and Al-Salem [22]. The return of products is addressed by Abdallah et al. [20], Diabat et al. [23] and Diabat et al. [24]. Specifically with respect to the closed loop supply chain, the generic bidirectional supply chain was introduced by Sahyouni et al. [25], where the authors present basic concepts pertaining to closed loop supply chains such as the decision of the location of product collection facilities and the allocation of returned product flows to such facilities. In order to solve the problem the authors employ Lagrangian relaxation and develop an algorithm that is both efficient and effective and through their results they discuss the implications of integrated decision making in the context of forward and reverse supply chains. More recently, Zhang et al. [26] study the capacitated facility location model with bidirectional product flows, where each distribution center is able to handle stocks of both new and returned products, thereby serving multiple roles. The authors model the problem as a mixed integer non-linear program (MINLP) that optimizes the location of distribution centers, as well as the assignment of retailers to distribution centers.

In the current work, we implement the integration of different decision levels, namely inventory management and facility location, in the context of the closed loop supply chain. The problem is modeled as a mixed integer non-linear program (MINLP), for which we reformulate some of the non-linear terms and develop a piecewise linearization. The contribution of our work can be largely attributed to the comprehensive formulation as well as the linearization developed which results in a formulation that is solvable exactly using CPLEX. The linearization demonstrates a very good performance, as will be seen in the section of the computational analysis where we provide a comparison with both the solution of the MINLP using commercial software and the solution obtained through the sequential rather than the integrated approach. Finally, managerial insights are provided by our sensitivity analysis with respect to the various weights attributed to the operational costs.

3. Model description

The current section presents the problem formulation, which combines the capacitated facility location and inventory management problem in a closed-loop supply chain described by a