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PRISM: PRIority based SiMulated annealing for a closed loop supply chain network design problem

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ABSTRACT

Concerns over environmental degradation, legislative requirements and growing needs of business have fueled the growth of Closed Loop Supply Chains (CLSC). We consider a CLSC and address the issues of designing the network and of optimizing the distribution. Four variants of the problem are considered. The problem is modeled as an Integer Linear Program (ILP). We develop a constructive heuristic based on Vogel's approximation method–total opportunity cost method to provide good initial solutions to a priority-based simulated annealing heuristic, to accelerate its convergence. Trials on a set of hypothetical datasets have yielded encouraging results. The methodology is also tested using a case study data of a company producing electronic products. Implications for sustainability are discussed.

1. Introduction

Objectives of supply chain management (SCM) have expanded over the last few decades, from minimizing costs or maximizing service to customer [3] to include minimizing adverse impact on environment. Today, Government legislations (End-of-Life vehicle, 2000 and WEEE, 2002), voluntary standards and customer expectations are making organizations accountable for the impact of their products and operations on the environment. Consumers demand eco-friendly products. Companies have begun to focus on economic and environmental liabilities at the product level as well as the operational level. Business demands have to be considered simultaneously with environmental concerns while operating the supply chains. The initiative of sustainable SCM (SSCM) is gathering momentum across the globe. Developed countries recognize the value of holding on to old and reusable goods [41]. Fig. 1 shows the facets of SSCM with three critical dimensions: closed loop supply chain (CLSC); green supply chain (GSC) and reverse logistics.

We focus on design of network and optimization of distribution for CLSC.

The focus of most of the research work on CLSC has been on the development of mathematical models for network design in CLSC with different network configurations. Only Refs. [24,30] seem to have addressed large network design problems in CLSC. They have developed heuristic methodologies for solving the problem. In this study, we consider a single-period, single product CLSC network with deterministic demands and uncertain product returns [34]. Four variants of the network are considered: two distribution planning scenarios and two location selection/distribution planning scenarios. We formulate ILP models for the four network variants considered. A constructive heuristic based on Vogel's approximation method–total opportunity cost (VAM–TOC) method and a priority-based simulated annealing search heuristic is developed to find near optimal solution for the problem. The initial solution given by the constructive heuristic helps faster convergence of the search heuristic. A decoding algorithm with recursive cost function is developed to solve this multi-stage supply chain problem. Finally, the implication on sustainability in using a dedicated warehouse supply is discussed.

The remainder of the paper is organized as follows: Section 2 provides a review of literature. In Section 3, we describe the problem and its variants considered for study and propose an integer linear program (ILP) for the problem in Section 4. In Section 5, the solution methodology comprising a constructive heuristic and a PRIority based SiMulated annealing enhanced by the constructive heuristic (PRISM) are presented. Computational results on hypothetical datasets and a real life case study are discussed in Section 6.

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Fig. 1. Facets of sustainable supply chain management.

Section 7 presents some conclusion on the work and future research directions.

2. Literature review

Literature on integrated forward/reverse logistics models for CLSC is categorized based on products and periods (one or many). A discussion of various models and methodologies adopted under each category follows.

2.1. Single period, single product models

Jayaraman et al. [13] considered remanufacturing of products and developed a 0–1 MIP model (REVLOG) for a single period network to assist decisions on logistics and selection of locations. Fleischmann et al. [6] proposed a Recovery Network design Model (RNM) to assist location/allocation decisions for a single period, single product integrated forward/reverse network. Krikke et al. [18] developed a single period, multi-objective mixed integer linear programming (MILP) model, akin to a weighted goal programming approach. Salema et al. [33] developed an MILP for an un-capacitated network with single product and capacitated network with multiple products. Lu and Bostel [20] developed an un-capacitated, single period facility location model for remanufacturing network system and proposed a heuristic based on Lagrangian relaxation. Lee and Dong [19] considered the case of computer products at the end of their lease and proposed a Mixed Integer Programming (MIP) model and a two-stage heuristic approach to solve the problem. Pishvaee et al. [25] proposed a stochastic MILP (SMILP) model incorporating uncertainties in costs, demand and return percentage. Wang and Hsu [43] proposed a generic ILP model for a closed-loop network structure. A spanning tree-based GA was employed to deal with problems of higher computational complexity. Pishvaee et al. [24] developed a bi-criteria (cost and responsiveness), single period, MIP for a CLSC network and proposed a memetic algorithm to solve it.

2.2. Single period, multi product

Halit et al. [11] considered a multi-product CLSC network design problem and proposed a Benders decomposition (BD) approach for solving the problem. From the RNM of Ref. [6], Salema et al. [34] considered uncertain demand and return and proposed an MILP for multi-product reverse logistics network for capacitated recovery center and factory/warehouse-location decisions. Du et al. [4] developed a Mixed Integer Non Linear Programming (MINLP) model for a closed loop network structure with capacity expansion and a differential evolution algorithm to solve random test instances. Subramanian et al. [40] developed a generalized location/allocation ILP model for multi-echelon, single period, multi-product, closed loop supply chain network.

2.3. Multi period, single product

El-Sayed et al. [5] modeled a multi-period, multi-echelon, forward–reverse logistics network as an SMILP model with stochastic demand in customer zones.

2.4. Multi period, multi product

Ko and Evans [17] developed an integrated forward-reverse multi-period, two-echelon, multi-product, capacitated location model operated by 3PLs. MINLP model and genetic algorithm (GA) were developed to solve random test instances. Kannan et al. [14] designed an integrated forward logistics multi-echelon distribution inventory supply chain model (FLMEDIM) and closed loop multi-echelon distribution inventory supply chain model (CLMEDIM) for a build-to-order environment using GA and particle swarm optimization. However, there are limitations and errors in the model, in the data sets and in the computational studies reported [29,39]. Salema et al. [36] developed a multi-period, multi-product CLSC network model considering strategic and tactical planning time horizons and improved the model further [35]. Both models address simultaneous design and planning of supply chains in strategic and tactical planning time horizons. Kannan et al. [15] investigated the optimal usage of secondary lead recovered from spent lead–acid batteries for producing new batteries. They developed GA, based on heuristics, to solve the multi-echelon, multi-period, multi-product closed loop supply chain network model for making decisions on material procurement, production, distribution, recycling and disposal.

Our review of literature indicates that there is scope for further work on CLSC models. We develop a comprehensive CLSC model, with and without the consideration of fixed charge for locating facilities, dedicated warehouse to mobilize returns efficiently and include uncertainty in products returns. The present problem falls under the class of multi-stage transportation in CLSC environment. The objective is to optimize the design of a CLSC network and the distribution of products across the forward and reverse supply paths. In this study, we develop a mathematical model, a constructive-heuristic based on VAM–TOC method and a PBSA search heuristic which is enhanced by the constructive heuristic. Four variants of the problem are studied. The reduction in damage to environment as a consequence of the network design is also discussed.

3. The model

A network design model for a single product, single period CLSC is presented in this section. Let $S=\{1,2...,n_S\}$ be the set of suppliers, $I=\{1,2,...,n_I\}$ be the set of raw materials for producing the product, $M=\{1,2...,n_M\}$ be the set of manufacturing facilities, $D=\{1,2...,n_D\}$ be the set of distribution hubs, $W=\{1,2...,n_W\}$ be the set of warehouses, $R=\{1,2,...,n_R\}$ be the set of retailers, $Z=\{1,2,...,n_Z\}$ be the set of recycling plants, and $Y=\{1,2,...,n_Y\}$ be the set of disposal sites. Fig. 2 shows the CLSC network considered in the study.

Manufacturers produce a product P using a set of raw materials I purchased from S suppliers. Retailers face a deterministic demand for product P. Customers return used products to retailers [37]. The products are subsequently returned to the manufacturers through the return channel. On the return path, one portion of the products is disposed off as unusable and another portion is