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Designing a sustainable closed-loop supply chain network based on triple bottom line approach: A comparison of metaheuristics hybridization techniques

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ABSTRACT

Recently, there is a growing concern about the environmental and social footprint of business operations. While most of the papers in the field of supply chain network design focus on economic performance, recently, some studies have considered environmental dimensions.

However, there still exists a gap in quantitatively modeling social impacts together with environmental and economic impacts. In this study, this gap is covered by simultaneously considering the three pillars of sustainability in the network design problem. A mixed integer programming model is developed for this multi-objective closed-loop supply chain network problem. In order to solve this NP-hard problem, three novel hybrid metaheuristic methods are developed which are based on adapted imperialist competitive algorithms and variable neighborhood search. To test the efficiency and effectiveness of these algorithms, they are compared not only with each other but also with other strong algorithms. The results indicate that the nested approach achieves better solutions compared with the others. Finally, a case study for a glass industry is used to demonstrate the applicability of the approach.

1. Introduction

Supply Chain Network Design (SCND) as a strategic decision plays the main role in the performance of a supply chain. SCND contains the determination of locations, numbers and capacities of network facilities as well as the material flow through the network. The configuration of the logistics network cannot be changed in short term as its change is very costly and time-consuming. SCND is also a crucially important decision, as it constrains the subsequent tactical and operational decisions.

While for many years, minimizing the total cost or maximizing the profit was the main objective of supply chains, nowadays, they are responsible for the environmental impacts of their products and operations, the health and safety of their employees and the whole society. In this way, activists, Non-Governmental Organizations (NGOs) and media are demanding the firms to take the responsibility of not only their own actions but also other partnersin the supply chains. Moreover, governments have enacted legislations in favor of the environment such as regulations for greenhouse gases (GHGs) reduction in European Union, Australia and Canada.

All in all, supply chains are shifting toward Sustainable Supply Chain Management (SSCM) with various motivations such as gaining public image (Fombrun, 2005), satisfying activists' requirements (Spar & La Mure, 2003), and maintaining customers for long term (Bhattacharya & Sen, 2004). Sustainable Supply Chain Management (SSCM) is defined as the consideration of environmental and social impacts of supply chain operations as well as its economic performance in the management of information, material and capital flow (Seuring & Müller, 2008). Accordingly, there is a gap in the previously published papers in the area of logistics network design. These papers lack in the simultaneous consideration of triple bottom lines of sustainability which can be attributed to the complexity of modeling social impacts and to some extent environmental aspects.

Based on the aforementioned considerations,this paper addresses the issue of multi-objective, multi-echelon logistics network design including suppliers, plants, distribution centers, retailers, customer zones, collection/inspection centers and recycling. This model can be distinguished from the previous studies in the following directions. Firstly, the social dimension of sustainability is quantified and embedded as a distinct objective besides total costs and environmental impacts. Secondly, the forward and reverse logistics are integrated in a general Closed Loop Supply Chain (CLSC) model. Finally, it should be noted that logistics

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network design is an NP-hard problem (Eckert & Gottlieb, 2002; Jo, Li, & Gen, 2007; Syarif, Yun, & Gen, 2002). Thus, we have developed and compared three novel metaheuristics called nested, hybrid, and two-phase to find Pareto-optimal solutions.

The paper is organized as follows. Relevant previous researches are reviewed in Section 2. In Section 3, the problem is described in detail. In Section 4, the optimization technique and characteristics of metaheuristics are explained, respectively. Experimental evaluations are conducted to evaluate the performance of the proposed algorithms against each other in terms of different criteria in Section 5. Section 6 is devoted to the case study. Finally, Section 7 presents the main conclusions and future lines of research.

2. Literature review

Recently, sustainability has intrigued both researchers and practitioners. In this way, Tang and Zhou (2012) has reviewed recent operations research/management science research developments in the domain of environmentally and socially sustainable operations. Brandenburg, Govindan, Sarkis, and Seuring (2014) has reviewed quantitative models that address sustainability aspects in the forward supply chain. While for decades, a lot of papers have focused on SCND, due to the increasing importance of sustainability, some articles have considered environmental and/or social impacts of SCND as additional objective(s) for multi-objective SCND (Chaabane, Ramudhin, & Paquet, 2012; Chen, Govindan, & Golias, 2013; Dehghanian & Mansour, 2009; Elhedhli & Merrick, 2012; Fonseca, García-Sánchez, Ortega-Mier, & Saldanha-da-Gama, 2010; Govindan, Jafarian, Devika, & Khodaverdi, 2014; Kannan, Diabat, Alrefaei, Govindan, & Yong, 2012; Pishvaee, Torabi, & Razmi, 2012b; Wang, Lai, & Shi, 2011a). In this paper, we review specific related SCND problems for forward, reverse and closed-loop SCND problems.

According to Tables 1 and 2, most of the previous researches have utilized Mixed Integer Programming (MIP) to model the problem. These models range from simple single objective forward facility location models (e.g. Jayaraman & Pirkul (2001)) to complex multi-objective closed-loop models (e.g. Chaabane et al. (2012)).

Elhedhli and Merrick (2012) have considered emission costs alongside fixed and variable location and production costs in a forward SCND problem. They have used a concave function to model the relationship between CO_2 emissions and vehicle weight. As the direct solution of their proposed model is not possible, Lagrangian relaxation is used to solve it Wang et al. (2011a) have considered the environmental concerns of forward SCND by proposing a multi-objective optimization model that captures the trade-off between the total costs and the environmental impacts. Pishvaee et al. (2012b) proposed a credibility-based fuzzy mathematical model for a forward supply chain network with three stages. Their model aims to minimize both the environmental impacts and the total costs. They showed the applicability of the model as well as the usefulness of the solution method in an industrial case study.

Recently, the importance of collecting and treating end-of-life (EOL) products has increased substantially. Sasikumar and Kannan (2008a,2008b, 2009) and Pokharel and Mutha (2009) overviewed various aspects of Reverse Logistics (RL). Accordingly, design of RL networks has interested researchers considerably (Kannan et al., 2012; Srivastava, 2008). Pishvaee, Kianfar, and Karimi (2010) developed a mixed integer linear programming model for a multistage RL network in which both opening and transportation costs have been taken into account. Since the model is NP-hard, they have proposed simulated annealing algorithm with special neighborhood search mechanisms. Kannan et al. (2012) considered the environmental impacts of the RL network model proposed by Pishvaee et al. (2010) by appending a carbon footprint term to the objective function. They tested their model with a case study in a plastic industry. Fonseca et al. (2010) developed a bi-objective model in which total costs and environmental impacts of an RL network are taken into account. By using a two-stage stochastic programming, the uncertainty of both shipping costs and waste generation amount is captured in their model. They applied the model for a case in the province of Cordoba.

To avoid the sub-optimality which arises in separate modeling of forward and reverse networks, many researchers have integrated forward and reverse network design known as closed-loop SCND (CLSC) (Soleimani, Esfahani, & Govindan, 2013). Fleischmann, Beullens, Bloemhof-Ruwaard, and Van Wassenhove (2001) suggested a Mixed Integer Linear Programming (MILP) model for designing a CLSC. They showed that often RL operations can be efficiently integrated into existing forward logistics. Schultmann, Zumkeller, and Rentz (2006) considered EOL vehicle treatment in Germany. They concentrated on the flow of used products and reintegrated reverse flow of used products into their genuine supply chains. They have modeled RL with vehicle routing planning and finally have used Tabu search (TS) to solve the model.

Wang and Hsu (2010) have integrated environmental issues in an integer CLSC model and also have developed a genetic algorithm (GA) based on a spanning tree structure to solve the propounded NP-hard model. Pishvaee and Razmi (2012) proposed a multi-objective fuzzy mathematical programming model for designing an environmental supply chain under inherent uncertainty of input data in such problem. They applied Life Cycle Assessment (LCA) method to quantify the environmental influence of the network.

Due to the plethora of literature about SCND, in Table 2 we have classified the published literature according to six main features: type of network, objectives, modeling, logistics network stages, model outputs and solution method. To summarize Table 2, a coding system is presented in Table 1 by which the literature is reviewed in Table 2.

As shown in Table 2, minimizing the cost of the network is the most common objective in the surveyed models and recently a few papers have dealt with sustainable network design.

As most of the network design problems are NP-hard, numerous solution methods including heuristics, metaheuristics and Lagrangian-based methods are developed. Due to the importance of the solution methods, the last column of Table 2 depicts the solution methods.

As it is depicted in Table 2, only Dehghanian and Mansour (2009) and Pishvaee, Razmi, and Torabi (2012a) have proposed models in which social impacts of SCND have been taken into account. However, our work can be distinguished from previous papers. Firstly, we try to quantitatvely model different social aspects alongside environmental and economic aspects in a single MILP model. Secondly, while Dehghanian and Mansour (2009) and Pishvaee et al. (2012a) model forward and reverse networks, respectively, our model investigates closed-loop network. Last but not least, novel metaheursitc algorithms are proposed and compared to solve this complex model.

3. Problem description

In this paper, as illustrated in Fig. 1, we introduce an MILP formulation for a CLSC network design problem with ten echelons. The proposed model emphasizes the treatment process by considering four types of facilities called treatment centers in the reverse network: (i) *Recovering*: the EOL products are recovered for reuse; (ii) *Remanufacturing*: the EOL products are remanufactured and prepared for reuse; (iii) *Recycling*: the EOL products are recycled and they are used for manufacturing new products; and (iv) *Disposal*: the EOL products are completely disposed as their quality is too low for manufacturing.