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Multi-period design and planning of closed-loop supply chains with uncertain supply and demand

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ABSTRACT

A design and planning approach is proposed for addressing general multi-period, multi-product closed-loop supply chains (CLSCs), structured as a 10-layer network (5 forward plus 5 reverse flows), with uncertain levels in the amount of raw material supplies and customer demands. The consideration of a multi-period setting leads to a multi-stage stochastic programming problem, which is handled by a mixed-integer linear programming (MILP) formulation. The effects of uncertain demand and supply on the network are considered by means of multiple scenarios, whose occurrence probabilities are assumed to be known. Several realistic supply chain requirements are taken into account, such as those related to the operational and environmental costs of different transportation modes, as well as capacity limits on production, distribution and storage. Moreover, multiple products are considered, which are grouped according to their recovery grade. The objective function minimizes the expected cost (that includes facilities, purchasing, storage, transport and emissions costs) minus the expected revenue due to the amount of products returned, from repairing and decomposition centers to the forward network. Finally, computational results are discussed and analyzed in order to demonstrate the effectiveness of the proposed approach. Due to the large size of the addressed optimization problem containing all possible scenarios for the two uncertain parameters, scenario reduction algorithms are applied to generate a representative, albeit smaller, subset of scenarios.

1. Introduction

Nowadays modern industrial enterprises are operating in a business environment undergoing significant transformations that introduce new and important challenges. These involve market changes (e.g. higher competition, changeable product specifications and shorter product life cycles), new regulations for the recovery and recycling of end-use products, and the need of an increasing sustainability of the whole operation, including a reduction of environmental and social impacts. Thus, in order to ensure a profitable operation of their supply chains, enterprises need to address the ensuing challenges.

The constantly shifting and increasing customer requirements are the major challenges due to their direct effect on production systems performance (Gupta & Maranas, 2003). Thus, as pointed out by Papageorgiou (2009), the need to account for this source of uncertainty has widely been recognized as an increasingly important issue. In general, different sources can be identified, such as product price and demand, production and transport costs, raw material accessibility, etc. Optimization approaches handling uncertainty considerations are then very advantageous. Nevertheless, such approaches lead to very large-scale models due to parameters with large uncertainty spaces. Reviews on optimization techniques to deal with uncertainty in the structuring and managing of corporations and their processes, can be found in Sahinidis (2004) and Li and Ierapetritou (2008).

The increasing need for remanufacturing due to resources shortage, environmental deterioration and new regulations, requires companies to organize their activities in order to explore and take full advantage of the coordination of forward and reverse material flows. Closed-loop supply chains (CLSC) extend the traditional definition of supply chains by explicitly exploring the synergy between the two flows. Thus, CLSC involves issues associated to new, end-use and remanufactured products, creating an added challenge for the design and planning problem. Therefore, practitioners and academics are paying an increasing interest to CLSCs, aiming to collect and recycle used products, with the objective of linking together environmental issues and business opportunities (Guide & Van

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Wassenhowe, 2009). In recent years, the sustainability of supply chains (SCs) along with their associated environmental and social impacts have received increasing attention (Srivastava, 2007), giving rise to a more comprehensive concept of sustainability, which now integrates economic, environmental and societal issues. Thus, the development of integrated frameworks for supply chain management (SCM) is a necessary condition for achieving sustainable supply chains. These frameworks should also account for an important economic facet of sustainable SCs, that is the capability of offsetting disturbances, such as in the present case the supply and demand fluctuations, by reducing readily the impact they cause on their performance. As a result, the number of works dealing with aspects of the sustainable SCM problem and with the systematic incorporation of environmental aspects in more traditional approaches, has started to grow (Côté, Lopez, Marche, Perron, & Wright, 2008; Duque, Barbosa-Povoa, & Novais, 2010; Georgiadis & Besiou, 2008; Hugo & Pistikopoulos, 2005; Ilbery & Maye, 2005; Pinto-Varela, Barbosa-Póvoa, & Novais, 2011).

The importance of environmental factors is also reflected in the explicit and increasing consideration given to the improvement of methodologies and indicators for environmental impact assessment (Corbett & Kleindorfer, 2003). Environmental indicators have been used for explicit inclusion in the SCs of such factors as waste from all network processes and greenhouse gas emissions. Paksoy, Bektas, and Özceylan (2011) state that greenhouse gas emissions, and CO_2 in particular, are by far the most prominent factors with respect to hazardous consequences on human health. In addition, these authors remark that one important source of greenhouse gas emissions in SCs come from the transportation activities between network entities.

The features that distinguish this paper from the existing bibliography include the investigation of the impact of supply and demand uncertainties on the design and planning problem of a generic multi-product multi-period CLSC, structured as a 10-layer network. In particular, the formulation considers multi-period multi-commodity problems and uncertain conditions varying during the planning horizon. In addition, the approach takes into account environmental impact, mainly in the form of CO_2 emissions, deriving from the transportation of material/products in both the forward and reverse networks. All these features, considered as part of the addressed problem, have been traditionally reported in the literature as being handled separately and few attempts have been made to comprehensively integrate these aspects simultaneously.

The rest of this article is organized as follows. In the next section, relevant literature on CLSC design and planning under uncertainty is reviewed. Section 3 states both the underlying problem assumptions and the details of the approach in order to make it flexible in representing a wide variety of network configurations. In Section 4 a mathematical model is proposed for the multi-period, multi-product CLSC design and planning problem with uncertain levels in the amount of raw material and customer demands. In Section 5, to highlight the benefits of such a formulation, a case-study is presented based on the example introduced by Paksoy et al. (2011), which is modified in order to illustrate the application of the multi-period multi-product stochastic formulation. In Section 6, a parametric and scenario analysis is performed to show the benefits of a stochastic model based on scenarios, as opposed to its static counterpart. The computational experiments also allow deriving a number of managerial insights about the network configuration with respect to changes in relevant SC parameters.

2. Overview of the literature

In this section a selective summary of relevant papers related to the approach proposed in this work is presented. A comprehensive review of a wide variety of models and case studies in reverse and closed-loop logistics network design can be found in Aras, Boyaci, and Verter (2010).

In the last decade, many researchers have been working in order to gradually obtain more comprehensive and computationally tractable approaches that can better capture the essence of many CLSC networks. This can be seen in some papers such as Shapiro (2004), Papageorgiou (2009) and Melo, Nickel, and Saldanha da Gama (2009). It becomes clear that many characteristics of real-world relevance for CLSC management are still distant from being fully incorporated in the models available in the literature.

Few papers have been proposed considering stochastic programming approaches applied to CLSCs configurations under uncertainty. Some of the most relevant papers are: Salema, Barbosa-Póvoa, and Novais (2007), Listeş (2007), Francas and Minner (2009), Pishvaee, Jolai, and Razmi (2009), Lee and Dong (2009), Wang and Hsu (2010), Pishvaee, Rabbani, and Torabi (2011), Vahdani, Tavakkoli-Moghaddam, Modarres, and Baboli (2012), Zeballos, Gomes, Barbosa-Povoa, and Novais (2012), Amin and Zhang (2013) as well as Cardoso, Barbosa-Póvoa, and Relvas (2013).

Salema et al. (2007) proposed a MILP model to deal with the design of a reverse logistic network with capacity limits, one-period planning horizon, multi-product management and scenarios to deal with the uncertainty on product demand and return. Listeş (2007) proposed a similar model but with a solution algorithm based on Benders decomposition. Francas and Minner (2009) accounted for uncertainty in demand and return considering two different fixed network structures and two different market structures. The authors studied capacity investment from a network perspective in a single-period problem. Pishvaee et al. (2009) proposed a scenario-based stochastic optimization model for a single-product, single-period forward and reverse logistics networks considering production/recovery, hybrid distribution/collection centers, customers, and disposal centers. In their formulation, the demand, quantity and quality of return flows and variable costs are assumed to be uncertain. Lee and Dong (2009) proposed a two-stage stochastic programming model for the design of a multi-period CLSC network. Uncertainty is considered in the demand of forward products and in the supply of returned products at customers. Since optimization mathematical techniques are computationally incapable to obtain solutions due to the problem size and complexity, those authors developed a heuristic algorithm based on simulated annealing. Wang and Hsu (2010) developed an interval programming model where the uncertainty was expressed by fuzzy numbers. Results were obtained considering that customer demand and recovery rate are uncertain parameters. Pishvaee et al. (2011) proposed a robust optimization model to determine the number and location of collection/inspection, recovery and redistribution centers, and the quantity of flows between each pair of network entities, in a single-product setting. In addition, the problem considered in the paper includes customers at a first and second market, and the following uncertain parameters: quantity of returned products from the first market customers, second market customers' demands and transportation costs. Vahdani et al. (2012) developed a fuzzy multi-objective robust formulation which minimizes the total costs and the expected transportation costs after failure of facilities in a logistics network. Zeballos et al. (2012) introduced a two-stage scenario-based modeling approach in order to deal with the design and planning decisions in multi-period, multi-product CLSCs subject to uncertain conditions. In their paper, uncertainty is associated to the quantity and quality of the flow of products of the reverse network. Amin and Zhang (2013) proposed a mixed-integer linear stochastic programming model (scenario-based) for a single-period multi-product CLSC location problem including multiple plants, collection centers and demand markets. The model considers demand and returns as uncertain