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Multi-objective optimization of environmentally conscious chemical supply chains under demand uncertainty

R. Ruiz-Femenia [a], G. Guillén-Gosálbez [b,*], L. Jiménez [b], J.A. Caballero [a]

[a] Departamento de Ingeniería Química, Universidad de Alicante, Apartado de Correos 99, Alicante 03080, Spain
[b] Departament d'Enginyeria Química, Universitat Rovira i Virgili, Av. Països Catalans, 26, 43007 Tarragona, Spain

HIGHLIGHTS

- ▸ The proposed solution guide decision-makers towards more sustainable process alternatives.
- ▸ The stochastic design for the supply chain improves the deterministic one.
- ▸ The worst case for the environmental objective is a suitable risk management metric.

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ABSTRACT

In this work, we analyze the effect of demand uncertainty on the multi-objective optimization of chemical supply chains (SC) considering simultaneously their economic and environmental performance. To this end, we present a stochastic multi-scenario mixed-integer linear program (MILP) with the unique feature of incorporating explicitly the demand uncertainty using scenarios with given probability of occurrence. The environmental performance is quantified following life cycle assessment (LCA) principles, which are represented in the model formulation through standard algebraic equations. The capabilities of our approach are illustrated through a case study. We show that the stochastic solution improves the economic performance of the SC in comparison with the deterministic one at any level of the environmental impact.

1. Introduction

Supply chain management (SCM) aims at the efficient integration of suppliers, manufacturers, warehouses and stores, in order to ensure that products are manufactured and distributed in the right quantities, to the right locations, and at the right time thereby maximizing the system's performance (Simchi-Levi et al., 2000). Traditional SCM performance indicators focused on quantifying the economic outcome (Beamon, 1999). In the last decade, the incorporation of environmental concerns along with economic criteria in the decision-making process has gained wider interest (Grossmann and Guillén-Gosálbez, 2010). This trend has motivated the development of systematic methods for reducing the environmental impact in SCM. Among the tools that are available, those based on multi-objective optimization (MOO) have been increasingly used for this purpose, mainly because they treat environmental aspects as additional objectives rather than as constraint imposed on the system. This approach therefore allows identifying solutions where significant environmental savings are obtained at a marginal increase in cost.

The scientific community has not yet reached an agreement on the use of a universal indicator for objective environmental impact assessment. It has become clear, however, that the environmental performance should be assessed over the entire life cycle of a process in order to avoid local solutions that shift environmental burdens from one echelon of the supply chain to another. Life cycle assessment (LCA) is a methodology that arose in response to this situation. LCA is a quantitative performance tool for evaluating the environmental loads associated with a product, process, or activity over its entire life cycle ('from the cradle to the grave') (Guinée et al., 2001). LCA adopts a holistic view that considers all material and energy flows that enter or exit the system. These flows include material and energy resources, as well as emissions to air, water and land, which are referred to as environmental burdens. These burdens are generated by activities encompassing extraction and refining of raw materials, transportation, production, use and waste disposal of final products. The combined use of LCA and MOO was formally

* Corresponding author. Tel.: +34 977558618; fax: +34 977 55 9621.
E-mail address: gonzalo.guillen@urv.cat (G. Guillén-Gosálbez).

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defined by Azapagic and Clift (1999), and since then has found many applications in a wide variety of environmental problems (for a review see Grossmann and Guillén-Gosálbez, 2010). Among these applications, the environmentally conscious design of chemical SCs has been the focus of an increasing interest in the last years. In a seminar paper, Mele et al. (2005) addressed the optimization of SCs with economic and LCA-based environmental concerns through a combined simulation-optimization approach. Hugo and Pistikopoulos (2005) proposed a MILP formulation for the long-range planning and design of SCs, in which the environmental performance was measured via the Eco-indicator 99 (Goedkoop and Spriensma, 2001). Bojarski et al. (2009) introduced an MILP formulation for the design and planning of SCs considering economic and environmental issues, which incorporated the CML 2001 methodology to assess their environmental performance. Guillén-Gosálbez and Grossmann (2009) (see also Grossmann and Guillén-Gosálbez, 2010) proposed two MINLP formulations for the design of chemical SCs under uncertainty that explicitly consider the variability of the life cycle inventory of emissions and damage assessment model, respectively.

Most of the works that combine MOO and LCA rely on deterministic approaches (Applequist et al., 2000; Simchi-Levi et al., 2000; Talluri and Baker, 2002; Guillén et al., 2006a) that assume that all model parameters are nominal and show no variability. In practice, however, it might be difficult to perfectly know in advance several key parameters, such as product demand, prices and availabilities. These parameters should be thus regarded as uncertain. Chemical process industries, in particular, are affected by many uncertainty sources that influence their economic and environmental performance (Sahinidis, 2004). In this context, deterministic models that neglect these uncertainties may lead to solutions that perform well in the most likely scenario but show poor performance under other plausible circumstances (Guillén-Gosálbez and Grossmann, 2009).

The most important and extensively studied source of uncertainty in SCM has been the demand (Gupta and Maranas, 2000,2003; Gupta et al., 2000; Tsiakis et al., 2001; Balasubramanian and Grossmann, 2004; Sahinidis, 2004; Guillén et al., 2005,2006b,2006d,2006c; You and Grossmann, 2008; Ejikeme-Ugwu et al., 2011). This is due to the fact that meeting customer demand is what mainly drives most SC planning initiatives. Product demand fluctuations over medium-term (1-2 years) to long-term (5–10 years) planning horizons may be significant (Gupta and Maranas, 2000). Deterministic SC models fail to capture the effect of demand variability on the trade-off between lost sales and inventory costs.

To the best of our knowledge, the works by Guillén-Gosálbez and Grossmann were the only ones that studied the effect of uncertainties in the environmentally conscious design and planning of chemical SCs. Particularly, the authors developed mathematical programming tools that accounted for the variability of the life cycle inventory of emissions and characterization factors involved in the evaluation of the environmental performance of SCs (Guillén-Gosálbez and Grossmann, 2009,2010).

In this work, and as a step forward in our previous research, we study the effect of another uncertainty source (i.e., demand uncertainty) on the economic and environmental performance of SCs. Several previous works have studied this source of uncertainty in SCM, but to the best of our knowledge, there is no single contribution that has addressed its impact on both, the economic and environmental performance of SCs. We formulate the SC design problem under uncertainty as a multi-objective stochastic MILP that seeks to maximize the expected profit and minimize the probability of exceeding a given environmental limit. The capabilities of our approach are illustrated in the discussion of a case study that addresses the design of a petrochemical supply chain.

The remainder of this article is organized as follows. The problem of interest is first formally stated, and the assumptions made are briefly described. The problem data, decision variables and objectives are also introduced at this point. The stochastic mathematical model that considers explicitly the demand uncertainty is then presented. The solution procedure is described in the following section. The capabilities of the approach proposed are then illustrated through a case study based on a European petrochemical SC. The conclusions of the work are finally drawn in the last section of the paper.

2. Problem statement

In this work we consider a generic three-echelon SC (production-storage-market) as the one depicted in Fig. 1. This network includes: a set of plants with a set of available technologies, where products are manufactured; a set of warehouses where products are stored before being shipped to final markets; and a set of markets where products become available to customers.

The problem addressed in this article can be formally stated as follows. Given are a fixed time horizon divided into a set of time periods, a set of potential locations for the SC facilities, the capacity limitations associated with these technologies, the prices of final products and raw materials, the investment and operating cost of the SC and environmental data (emissions associated with the network operation and damage assessment model). The demand, which is assumed to be uncertain, is described through a set of scenarios with given probability of occurrence.

The goal of the study is to determine the configuration of the SC along with the associated planning decision that simultaneously maximize the expected total net present value (NPV) and minimize the environmental impact under demand uncertainty. Decisions to be made are of two types: structural and operational. The former include the number, location and capacity of the plants (including the technologies selected in each of them) and warehouses to be set up, their capacity expansion policy and the transportation links between the SC entities. The operational decisions are the production rate at the plants in each time period, the flows of materials between plants, warehouses and markets, and the sales of final products.

3. Stochastic mathematical model

Several methods have been proposed to deal with uncertainty in SCM. The most widely used approaches are control theory,

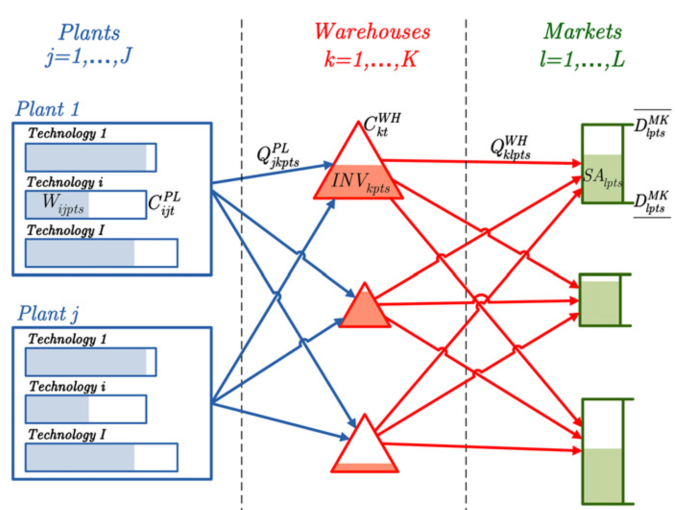

Fig. 1. Superstructure of the three-echelon SC taken as reference.