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Design of sustainable supply chains under the emission trading scheme

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ABSTRACT

Increase in environmental concerns together with legislations are forcing industries to take a fresh look at the impact of their supply chain operations on the environment. This paper introduces a mixed-integer linear programming based framework for sustainable supply chain design that considers life cycle assessment (LCA) principles in addition to the traditional material balance constraints at each node in the supply chain. Indeed, the framework distinguishes between solid and liquid wastes, as well as gaseous emissions due to various production processes and transportation systems. The framework is used to evaluate the tradeoffs between economic and environmental objectives under various cost and operating strategies in the aluminum industry. The results suggest that current legislation and Emission Trading Schemes (ETS) must be strengthened and harmonized at the global level in order to drive a meaningful environmental strategy. Moreover, the model demonstrates that efficient carbon management strategies will help decision makers to achieve sustainability objectives in a cost-effective manner.

1. Introduction

Supply chain network design attempts to define the best supply chain configuration that enables an organization to maximize its long-term economic performance. Typically, the decisions cover two planning levels: (1) strategic decisions on sourcing, production (opening or closing of facilities), distribution and sales; (2) tactical decisions on supply network planning affecting the flow of goods trough the network. Flexibility, robustness, and responsiveness are some of the strategies that have been used to adapt to dynamic changes in the supply chain environment (Sabri and Beamon, 2000). But, unfortunately the pursuit of short term profitability is still recognized as the one of the major drivers for managerial decisions and this, among other things, has contributed to the slowdown in the current global economy.

Nowadays, given the constraints relative to the availability of non-renewable resources (metal, oil, etc.), enterprises are more than ever obliged to rethink their strategies to ensure the sustainability of their operations. Closed-loop supply chains are one of the options that are being considered (Lieckens and Vandaele, 2007; Barker and Zabinsky, 2008; Srivastava, 2008; Pochampally et al., 2009). Other avenues being studied include different actions related to one or more phases of the product life cycle such as product design (Hugo and Pistikopoulos, 2005), production planning and control for remanufacturing (Jayaraman et al., 1999; Luo et al., 2001), inventory management (Ferretti et al., 2007), product recovery (Jayaraman, 2006), reverse logistics (Sheu et al., 2005; Sheu, 2008) and carbon emissions reduction (Ramudhin et al., 2008).

However, these actions may not be enough to guarantee long-term sustainability. Indeed, recovery of used products and re-processing (remanufacturing, recycling, disposal, incineration, etc.) might not only increase operating costs but also contribute to an increase in greenhouse gases (GHG) emissions which defeats long-term stainability. Sustainable development recognizes the interdependence between three dimensions: the economic, the environmental, and the social performances of an organization. An integrated approach that links supply chain decisions to the three pillars of sustainability is advocated.

Sustainable supply chain design (Frota Neto et al., 2008) is a new emerging approach that arose in response to this situation and tries to embed economic, environmental as well as societal decisions in supply chains at design time. The objective of the methodology proposed in this paper is to present a formal decision model that considers the important dimensions of sustainability throughout the supply chain life cycle.

2. Literature review

Traditionally, the main objective of optimization models used in strategic network design focused on the economic aspect of supply chains (Goetschalcks and Fleischmann, 2008). However, more recently there has been a growing awareness about environmental issues. The first proposals tried to integrate such considerations at the plant level. The main drawback of these approaches is that it may result in solutions that reduce the negative environmental

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impact somewhere in the supply chain at the expense of increasing it elsewhere.

Life Cycle Assessment (LCA) methodology has been proposed in response to this situation (De Benedetto and Klemes, 2009). LCA is a process for evaluating the environmental impacts associated with a product, process or activity. It identifies and quantifies the energy and materials used and the waste released to the environment, and evaluates and implements opportunities for environmental improvements. The assessment covers the entire life cycle of the product, process or activity, including extracting and processing raw materials, manufacturing, transportation and distribution, reuse and maintenance, recycling and final disposal.

Hugo and Pistikopoulos (2005) present a mathematical programming-based methodology with explicit inclusion of life cycle assessment (LCA) criteria as part of the strategic investment decisions related to the design and planning of supply chain networks. Nagurney et al. (2006) develop a supply chain model in which the manufacturers can produce homogeneous product in different manufacturing plants with distinct environmental emissions. Frota Neto et al. (2008) develop a framework for the design and evaluation of sustainable logistic networks where activities affecting the environment and cost efficiency in logistic networks are considered. Guillen-Gosalbez and Grossmann (2009) present a supply chain network design model to determine the supply chain configuration along with the planning decisions that maximizes the net present value and minimizes environmental impact. The model includes structural and planning decisions.

Suitable performance measures in evaluating the supply chain are important and directly affect their applicability (Gunasekaran et al., 2004). Various types of performance measures have been used to evaluate sustainable supply chain. Most frequently, they combine the economic performance with the environmental performance in order to find the trade-off between the two performances (Nagurney and Toyasaki, 2003; Pistikopoulos and Hugo, 2005; Sheu et al., 2005; Lu et al., 2007; Frota Neto et al., 2008; Guillen-Gosalbez and Grossmann, 2009). The economic dimension represents the cost or the profit in net present value (Pistikopoulos and Hugo, 2005). Various performance metrics have been developed to evaluate quantitatively the environmental impact of products, processes and activities such as the emissions of GHG (CO_2, CFC, NOx, ...) (Luo et al., 2001), waste generation (liquid or solid), energy use, and material recovery.

In recent years, different comprehensive environmental performance metrics has been proposed such as the "Eco-indicator 95" (Brentrup et al., 2001) "Eco-indicator 99" (Contreras et al., 2009), "Ecological Footprints", and "EcoPro" (Luo et al., 2001). These metrics are based on different methodological structures and weighting techniques where assumptions are different.

The applicability of different supply chain models have been tested in real industrial cases and in different fields: petrochemical production (Zhou et al., 2000), aluminum industry (Ferretti et al., 2007), personal computer (Min and Melachrinoudis, 1999; Dotoli et al., 2005, 2006), and the pulp and paper industry (Frota Neto et al., 2008). It shows particularly that numerous initiatives have provided incentives for organizations to become more sustainable. Some of these regulations are mandatory, but increasingly others are just voluntary environmental programs and considered as new alternatives for gaining or maintaining a competitive advantage. For instance, many industries are engaged in voluntary RL activities like the automotive industry (Schultmann et al., 2006), cellular telephones (Jayaraman et al., 1999), computers (White et al., 2003), pulp and paper industry (Frota Neto et al., 2008) because they can achieve additional profit.

While the LCA principle has been successfully applied to design new products and processes that reduce environmental damage (global warming, ozone depletion, acidification, toxicity, etc.), limited work has been conducted on the development of decision making models that integrate both LCA principles and supply chain management principles (Seuring and Muller, 2008). In addition, few studies have addressed the impact of integrating external control mechanisms on sustainable supply chain management practices such as environmental regulations, take-back legislation, GHG emissions, and carbon taxes, emission trading (Stranlund, 2007) and carbon markets (Johnson and Heinen, 2004; Peace and Juliani, 2009). For instance, Nagurney et al. (2006) is one of the first studies that addresses carbon taxes in the electric power supply chains (Nagurney et al., 2006). Subramanian et al. (2008) propose an approach to integrate environmental consideration within a managerial decision making framework. A non-linear mathematical programming model is introduced that allows the incorporation of traditional operations planning considerations (capacity, production and inventory) with environmental considerations (design, production and end-of-life). Decisions on the number of carbon credits purchased and sold in different periods are added under the limitation of carbon emissions.

Ramudhin et al. (2010) are the first to propose a carbon market sensitive strategic planning model for sustainable supply chain network design. They show that considerations of internal and external control mechanisms are of great importance to decision makers when designing sustainable supply chains. This paper extends the model presented in Ramudhin et al. (2010) by consideration of the LCA methodology to establish successful sustainable supply chains over time. The capability of the model is illustrated by an example of strategic planning in the aluminum supply chain.

3. Problem statement and methodology

Among the different approaches available to assess the environmental impact of processes and organizations, the LCA method seems to be the most promising. It aggregates the results of different aspects of environmental studies including GHG emissions that are recognized as the most harmful elements to the environment and responsible for climate change. GHG emissions are calculated based on emission factors and converted to carbon dioxide equivalent quantity (CO_2e).

Many countries are implementing various mechanisms to reduce GHG emissions including incentives or mandatory targets to reduce carbon footprint. Carbon taxes and carbon markets (emissions trading) are recognized as the most cost-effective mechanisms (Labatt and White, 2007). The basic idea is to put a price tag on carbon emissions and create new investment opportunities to generate a fund for green technology development (Bayon et al., 2007; Labatt and White, 2007). There are already a number of active carbon markets for GHG emissions such as the European Union Emission Trading Scheme (or EU ETS) in Europe, the largest multi-national GHG emissions trading scheme in the world, the New Zealand Emissions Trading Scheme (NZ ETS) in New Zealand, the Chicago Climate Exchange in United State (Johnson and Heinen, 2004; Peace and Juliani, 2009), and more recently the Montreal Climate Exchange in Canada.

Measuring and assessing carbon emissions becomes then an important step that can be achieved by LCA techniques and software (Rice et al., 1997). However, compliance with the environmental regulation of carbon emissions in a cost-effective manner is challenging. Thus, supply chain network design model had been revised to include the additional cost due to GHG emissions at all levels of the supply chain and social variables affecting the quality of life of the community in which the supply chain operates.

As shown in Fig. 1, an LCA based approach is necessary in order to establish the link between the critical inputs (raw material, energy, human, used product, etc.) and the output (products, GHG emissions, waste) at each node of the network over its entire life cycle. Strategic planning of sustainable supply chains should