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Mapping environmental issues within supply chains: a LCA based approach

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Abstract

This work addresses the optimization of Supply Chain (SC) planning and design considering economical and environmental issues. The SC operations model applied does not require a superstructure definition a priori for the material flows. The strategic decisions considered in the model are facility location and equipment allocation. For the environmental aspects of the problem a Life Cycle Assessment (LCA) approach is applied. IMPACT 2002+ methodology is selected to perform the impact assessment within the SC since it proposes a feasible implementation of a combined midpoint-endpoint evaluation. No aggregation of damage categories and analysis of partial environmental impacts for each of echelon are performed. The formulation leads to a multi-criteria MILP program. The criteria adopted as objective functions are damage categories impacts, overall impact factor and net present value (NPV). The main advantages of this model are highlighted through a case study of a maleic anhydride SC.
Keywords: Supply chain management, Life cycle analysis, Environmental management

1. Introduction

Supply Chain Management (SCM) has been a major source of competitive advantage in the global economy. Moreover, it is well recognized that an optimum management of the Supply Chain (SC) offers a key opportunity for preserving firm's value. A proper handling of SCM should be concerned with the sharing of responsibility from various aspects of performance which includes environmental matters. These issues are being considered recently by researchers. This sharing of responsibility calls for further research in the integration of environmental management with ongoing SC operations.

The aforementioned integration may be achieved through the emerging concept regarded as "Green Supply Chain Management" (GrSCM), defined as the integration of environmental thinking into SCM, including product design, material sourcing and selection, manufacturing/processing process selection, delivery of final product to the consumers as well as end of life management of the product after its useful life[1]. Traditionally, the optimization models devised to assist operation and design in the chemical processing industry have concentrated on finding the solution that maximizes a given economic performance indicator while satisfying a set of operational constraints imposed by the topology of the plant. In recent years, however, there has been a growing awareness of the importance of including environmental and financial aspects in the optimization procedure[2].

Several systematic methodologies are available for detailed characterization of the environmental impacts of chemicals, products, and processes. These methods include life cycle assessment (LCA), the methodology for obtaining Minimum Environmental Impact (MEI), the Waste Reduction (WAR) algorithm, the introduction of "eco-vectors" for the calculation of life cycle inventories for process industries and the Environmental Fate and Risk Assessment tool (EFRAT), to cite some of them.

LCA arose in response to the need of incorporating all the environmental contributions associated to a product or process system in one single framework. This framework includes the entire life cycle of the product, process or activity, encompassing extraction and processing of raw materials; manufacturing, transportation and distribution; re-use, maintenance recycling and final disposal. Most important is that LCA involves a holistic approach, bringing the environmental impacts into one consistent framework, wherever and whenever these impacts have occurred or will occur[3]. It can be clearly seen that LCA fits as a suitable tool for quantitatively assessing the environmental burdens of a SC.

SCM modeling and LCA share many drawbacks; the most important of them is data requirements needed to apply such quantitative calculations. In the case of LCA it is required to compile a Life Cycle Inventory (LCI) that involves the gathering of emission data from all echelons of the SC. In the case of SCM data is required for mass balance fractions, capacity consumptions, echelons and equipment connectivity, products demand, among others. In order to calculate an economic indicator, it is required to collect data about costs and prices. Regarding the environmental impacts calculated from the LCI, other LCA drawback is related to the calculation of potential impacts instead of actual impacts; this is mainly due to the temporal and spatial variability of the emissions. In the case of SC design and planning the quantitative indicators are further simplified considering aggregated figures. The data intensity of both techniques coupled to the simplification used in the calculation of the quantitative measures raise uncertainty issues. Despite the former mentioned drawbacks and the uncertainty issue both SCM and LCA are applied and information and decisions are taken from the interpretation of their results.

2. Problem statement

This work represents a further step to the approach initiated by Mele et al.[4] for assisting in the planning and design of a SC by considering economical and environmental impacts. The resulting model is solved by using a MILP optimization algorithm. Aggregation of damage categories is performed after optimization of each one of the impact categories. This action partially excludes the value-subjectivity inherent to the assignment of weights in the calculation of an overall SC environmental impact. Possible environmental tradeoffs between damage categories and the economic indicator could be observed by using a multi-objective optimization technique. The analysis of partial environmental impacts for every echelon is performed with the aim of discovering improvement opportunities; this analysis also provides information about where to focus emission control activity.

3. Mathematical formulation

The mathematical formulation derived to address the aforementioned problem is next briefly described. The variables and constraints of the model can be roughly classified into two groups. The first one concerns the process operations constraints given by the SC topology. The second one deals with the LCA methodology.

3.1. Design-planning formulation

The novel design-planning approach presented in this work is derived from the STN[5] formulation. The approach allows a model that does not require a superstructure definition a priori for the material flows. Hence, a facility may be used either as a processing or distribution site allowing the possibility of material flows between sites; such model behavior was not permitted in previous approaches.

$P_{ijff't}$ represents the batch size of task i in equipment j which receives input materials from site f and "delivers" output materials to site f' during period t. Indeed, a production task receives and delivers material within the same site. In case of distribution task, facilities f and f' must be different. The equations of the model are described in the next paragraphs.

The mass balance must be satisfied in each of the nodes that integrate the SC network. Eq. (1) represents the mass balance for each material (state) s consumed at each potential facility f in every time period t. Parameter α_{sij} is defined as the mass fraction of material s for task i performed in technology j. Equation (2) is added to control the changes in the capacities of the facilities over time. Equation (3) is included to update the total capacity ($FS_{j,f,t}$) by the amount increased during planning period t ($FE_{j,f,t}$). Equation (4) forces the total production rate in each plant to be greater than a minimum desired production rate and lower than the available capacity. Parameter β_{jf} defines utilization factor of technology j in site f, $\theta_{ijff'}$ determines the capacity consumption factor. Eq. (5) forces the amount of raw material r purchased from supplier e at each time period t to be lower than an upper bound given by physical limitations (A_{ert}). Also, the model assumes that part of the demand can actually be left unsatisfied because of limited production capacity. Thus, Eq. (6) forces the sales of product i carried out in market m during time period t to be less than or equal to demand.

$$\begin{aligned} S_{sft} - S_{sft-1} = \sum_{f'} \sum_{i\in T_s} \sum_{j\in(J_i\cap J_{f'})} \alpha_{sij} P_{ijf'ft} - \\ \sum_{f'} \sum_{i\in \bar{T}_s} \sum_{j\in(J_i\cap J_f)} \bar{\alpha}_{sij} P_{ijff't} \qquad \forall s,f,t \end{aligned} \tag{1}$$

$$V_{jft} FE^{L}_{jft} \le FE_{jft} \le V_{jft} FE^{U}_{jft} \qquad \forall f, j \in J_f, t \tag{2}$$

$$F_{jft} = F_{jft-1} + FE_{jft} \qquad \forall f, j \in J_f, t \tag{3}$$

$$\beta_{jf} F_{jft-1} \le \sum_{f'} \sum_{i\in I_j} \theta_{ijff'} P_{ijff't} \le F_{jft-1} \qquad \forall f, j \in J_f, t \tag{4}$$

$$\sum_{f'} \sum_{i\in IT_s} \sum_{j\in J_i} P_{ijff't} \le A_{sft} \qquad \forall s \in RM, f \in Sup, t \tag{5}$$

$$\sum_{f'} \sum_{i\in IT_s} \sum_{j\in J_i} P_{ijf'ft} \le Dem_{sft} \qquad \forall s \in FP, f \in M, t \tag{6}$$

3.2. Environmental formulation

Several impact characterization methodologies have been proposed. The methodology selected to carry out the Life Cycle Impact Assessment (LCIA) within the SC is IMPACT 2002+[6]. This methodology proposes a feasible implementation of a combined midpoint/damage-oriented approach. It links all types of LCI results via 14 midpoint categories (human toxicity, respiratory effects, ionizing radiation, ozone layer depletion, photochemical oxidation, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification/nitrification, aquatic acidification, aquatic eutrophication, land occupation, global warming, non-renewable energy, mineral extraction) to four damage categories (human health, ecosystem quality, climate change-global warming potential, resources). IMPACT 2002+ has grouped similar category endpoints into a structured set of damage categories by combining two main schools of impact model methods: Classical impact assessment methods (CML and EDIP) and damage oriented methods (Eco-indicator 99 or EPS). This approach contains the advantages of being able to calculate both mid and endpoint indicators, in this work, given our interest in the whole SC, only endpoints are calculated since these metrics are easier to understand compared to mid point values.

The equations of the environmental model are briefly described next. Equation (7), states the impact midpoint characterization associated to site *f*; ψ_{ija} is the a impact characterization factor for task *i* performed using technology *j*. In equation (8) all the midpoint interventions are combined into *g* damage categories using damage factors ς_{ag} and then normalized with $NormF_g$ factors. Equations (9) and (10) sum up the environmental damage category results for each site and for the whole SC, respectively.

$$IC_{af} = \sum_{t} \sum_{j \in J_f} \sum_{i \in I_j} \psi_{ija} P_{ijft} \qquad \forall a, f \tag{7}$$

$$DC_{gf} = \sum_{a \in A_g} NormF_g \zeta_{ag} IC_{af} \qquad \forall g, f \tag{8}$$

$$Impact_f^{2002} = \sum_{g} DC_{gf} \qquad \forall f \tag{9}$$

$$Impact_{overall}^{2002} = \sum_{f} \sum_{g} DC_{gf} \tag{10}$$

4. Case study

The case study used to illustrate the concepts behind the presented strategy addresses a SC design problem comparing different technologies for maleic anhydride (MA) production based on the oxidation of different hydrocarbon compounds (benzene and n-butane). MA is an important raw material used in the manufacture of phthalic-type and unsaturated polyester resins, copolymers, surface coatings, plasticizers and lubricant additives. The SC comprises raw material extraction facilities, processing sites, distribution centres and market places, fitting a cradle to distribution centre approach. Different raw material suppliers are modelled and the transportation network is restricted to Europe. Emissions inventory for all the SC echelons is retrieved from *Ecoinvent v1.3* database. Demand, costs and other economical data are based on current industrial trends. Several factors such as advances in catalyst technology, increased regulatory pressures, and continuing cost advantages of butane over benzene have led to a rapid conversion of benzene- to butane-based plants, consequently to the conversion of the whole MA SC.

Thirty-seven planning periods with a length of 1 month each are considered. The implementation in GAMS of the SC-LCA formulation leads to a MILP model with 24,791 equations, 147,832 continuous variables, and 1093 discrete variables. It takes 29 CPU s to reach a solution with a 0% integrality gap on an Intel Core 2 Duo computer using the MIP solver of CPLEX.

To explicitly show the tradeoff between the NPV and environmental impact (overall factor and damage factors), a multi-objective optimization is applied using the weighted sum method, taking into account in each case a pair of the aforementioned objectives. The dominated solutions obtained were filtered. The Pareto curves approximation obtained are shown in Figure 2. From these results, as expected, it is clear that conflict exists between environmental and economic issues. Lower environmental impacts are found associated to SCs configurations with lower NPV.

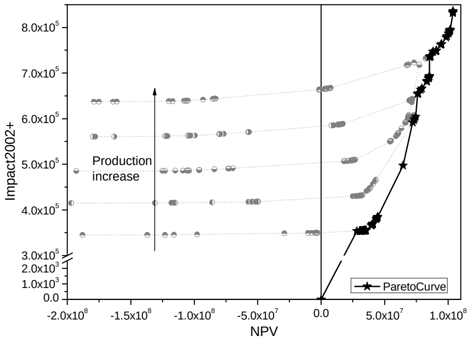


Figure 2. Overall impact vs. NPV Pareto curve (in gray iso-production curves)

As can be seen from Fig. 2 and 3, several SC structures are obtained when trading off NPV against the overall and each of the environmental indicators. Sixteen SC structures are found in total. In the case of the optimization of total environmental impact, only 5 structures are found. Being the most environmental friendly the one that manufactures MA from benzene and the most profitable the one that produces MA from n-butane feedstock. Other works related to SC design and environmental issues consider that demand is completely fulfilled. This assumption leads to an invariable total production rate and suboptimal solutions. In Fig. 2 iso-production curves correspond to solutions following this assumption. For the former cases minimum overall impact leads to negative NPVs. These solutions are obviously dominated by the zero-production solution (origin). The actual Pareto curve is shown in figure 2 as a continuous black line which is obtained by allowing unfulfilled demand. In figure 3 optimization of GWP, ecosystem quality, human health and resource depletion against NPV produces a set of completely dominated structures in terms of global environmental impact, as it was expected. It's interesting to note that in the case of GWP, there is a segment of the Pareto curve where diminishing this impact leads to a higher overall environmental impact.

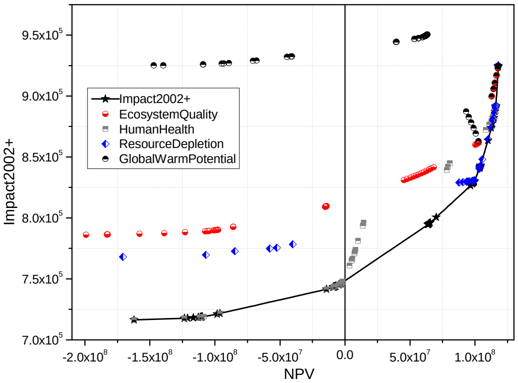
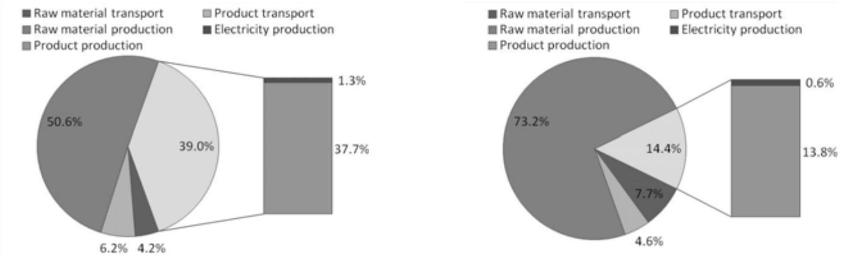


Figure 3. Calculated Overall impact of each impact optimization vs. NPV.

Figures 4a and 4b show the distribution of the environmental impacts in different SC echelons. In both cases raw material production is the most important factor contributing to the overall environmental impact, while electricity consumption is the least important aspect. In both cases improvements should be focused on technology for production of raw materials.



(a) Best environmental SC.

(b) Most profitable SC.

Figure 4 Distribution of environmental impacts

5. Final considerations and future work

The tradeoff analysis highlighted interesting scenarios where significant improvements activities should focus on. A SC for MA production based on benzene was found to be surprisingly more environmentally friendly than one based on n-butane, raw material production was found to be the most important contributor to overall environmental impact. Future work will focus on analyzing temporal distribution of emissions within this GrSCM proposed framework.

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