ENVIRONMENTALLY CONSCIOUS PROCESS PLANNING UNDER UNCERTAINTY

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Abstract

Waste minimization, pollution prevention and eco-efficiency are but a few phrases that are increasingly becoming established in the green process engineer's lexicon. While few argue with the fundamental ideal that the sustainable development philosophy promotes, the greatest challenge still remains the practical application of its principles in pursuit of technological innovations. In this paper, we aim to address this challenge by proposing a methodology for the explicit inclusion of environmental performance criteria as part of the strategic decisions associated with the long-term planning of investments in processing enterprises. Building upon our previous work, the deterministic environmentally conscious long-range planning problem is reformulated here as a classical two-stage stochastic programming model that can address the decision-making under uncertainty. Adopting a scenario-analysis approach within a multi-period framework it is possible to find a set of expected optimal solutions that hold over the stochastic outcomes. As such, the alternative supply chain configurations and production profiles, each achieving different compromises between financial benefit and environmental damage, can be compared to the worst and best case extremes.

Keywords

Long-range planning, Supply chain strategic design, Life cycle assessment (LCA), Multi-objective optimization, Uncertainty.

Introduction

Traditionally, strategic process selection decisions within a supply chain context have largely concentrated on improving market competitiveness by finding the optimal investment strategy and capacity plan that maximizes the return on the investment. Increasingly, there has been an awareness of the impact that extended production systems have on the environment, resulting in enterprise-wide management strategies such as product stewardship, life cycle assessment (LCA) and industrial ecology. However, despite the consensus about the relevance and benefits of adopting more sustainable business practices across entire product value chains, the greatest challenge still lies in the practical application of the environmental management strategies in pursuit of technological innovations.

To address this challenge we previously presented a deterministic model for the inclusion of explicit environmental performance criteria as part of the long-range investment planning and strategic design of supply chain networks (Hugo and Pistikopoulos, 2003). During these early stages of investment decision-making a manufacturing company has the earliest opportunity to influence *both* its future market competitiveness *and* its environmental performance.

Multi-objective optimization has become an established tool for trading off the various environmental concerns against the financial objectives. However, limited attention has been devoted to performing this type of multi-attribute decision-making under *uncertainty*, with

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some recent applications emerging in the areas of process design (Dantus and High, 1999), solvent selection (Kim and Diwekar, 2002) and waste treatment (Chakraborty *et al.*, 2003).

In this paper we build upon our previous work and reformulate the previously presented deterministic environmentally conscious long-range planning problem as a classical two-stage stochastic programming model that can address the decision-making under uncertainty. Adopting a scenario-analysis approach it is possible to find a set of expected Pareto optimal solutions in terms of the multiple conflicting objectives that holds over all the stochastic outcomes.

Deterministic Model Overview

Drawing upon past advances in the field of multi-product, multi-site supply chain network design (Tsiakis, *et al.*, 2001), chemical industry technology selection (Rudd *et al.*, 1981), long-range capacity planning (Sahinidis *et al.*, 1989) and process design for minimum environmental impact (Pistikopoulos, *et al.*, 1994), the environmentally conscious process selection problem considered here can be summarized as follows:

Given:

- a set of $m \in \mathcal{M}$ markets (distributors or customers) and their demands for a set of $i \in \mathcal{I}$ chemical products over a given long-term time period (planning horizon) $t \in \mathcal{T}$,
- a set of $j \in \mathcal{J}$ known chemical processing technologies (plants) to produce the desired products,
- a set of $s \in \mathcal{S}$ potential geographical sites for installing and expanding the capacities of the plants, and
- the availabilities of raw material feedstocks sold by a set of $r \in \mathcal{R}$ suppliers,

then the task is to:

- design the optimum supply chain network of the integrated production facilities that would satisfy the demand over the entire planning horizon

such that both the:

- net present value of the capital investment is maximized, and the
- impact that the entire network has on the environment is minimized.

More specifically, finding the optimum solution to this multiple criteria problem involves: (a) selecting the most appropriate technologies, (b) establishing their optimum capacity expansion policies and production profiles over time (c) allocating the technologies to the potential sites, (d) designing the product distribution network by assigning transportation links between the given markets and the selected sites, and (e) setting optimal plant production profiles and flows of materials between the various components within the supply chain.

Unlike most traditional approaches where only an economic criterion is considered, the model developed here also aims at finding the design that minimizes the environmental impact of the entire supply chain.

Quantifying the environmental performance of the enterprise requires an environmental impact assessment of the operations of the entire network over the entire planning horizon. This is achieved by adopting the principles of LCA and using a recently developed method of damage modeling, the Eco-Indicator 99 (Pré Consultants, 2000), to assess the environmental impact of the network. Guided by the scope and boundary definition step of LCA, the enterprise boundaries are expanded to incorporate a set of $c \in \mathcal{C}$ life cycle stages that includes the (a) production plants within the network, (b) transportation of raw materials to sites and products to markets, (c) generation and supply of utilities (electricity, thermal energy, *etc*.), (d) production of raw materials and (e) acquisition of natural resources.

Environmental burdens of each life cycle stage are characterized in terms of a set of $e \in \mathcal{E}$ impact categories/indicators representing various environmental concerns such as: (i) carcinogenic effects, (ii) respiratory illnesses caused by organic substances, (iii) respiratory illnesses caused by inorganic substances, (iv) climate change, (v) ozone layer depletion, (vi) ecotoxic emissions, (vii) acidification and eutrophication, (viii) extraction of minerals, and (ix) extraction of fossil fuels.

Each impact indicator is also classified under one the three main damage categories, $n \in \mathcal{N}$:={*Human Health Ecosystem Quality, Resource Depletion*}, through the multi-dimensional set $\mathcal{L}_{en}$. Finally, arriving at the measure of environmental performance, requires the normalization of the impacts and then the aggregation of these normalized categories into a single Eco-Indicator 99 Score.

Mathematically the formulation results in a multi-objective mixed integer linear programming (MOMILP) problem. The solution to the multi-objective optimization model is the set of trade-off solutions commonly referred to as the efficient or Pareto set of solutions. By definition, a point is said to be efficient (or Pareto optimal) such that any other point within the set improves the value of one objective function while compromising at least one other objective. One way of obtaining this set of efficient solutions is by reformulating it as a parametric programming problem (Dua and Pistikopoulos, 2000).

Two-Stage Stochastic Model Formulation[1]

The formulation previously presented assumes that the product demands and raw material availabilities can be accurately forecasted into the future horizon. However, because of the very nature of the problem being addressed, *i.e.* process selection and planning over a long-term horizon, it can be expected that demands and availabilities will be subject to considerable variability and can,

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[1] For brevity, only selected equations are presented

therefore, not be predicted with the desired level of certainty. Instead it is necessary to reformulate the model to address this uncertainty.

Two-stage stochastic formulations with recourse has become a popular approach within the stochastic programming domain for representing sequential decision-making problems under uncertainty. In particular, scenario planning is the commonly preferred choice for capturing the variability that can be expected in long-term trends. By capturing the uncertainty as a set of discrete realizations, a number of possible scenarios are predicted, with the goal being then to find a robust solution that optimizes the expected objective over the entire set of plausible scenarios. While this approach offers an attractive way to practically manage the uncertain forecasts, it adds significantly to the computational complexity since many scenarios inevitably leads to large-scale problems (Ahmed, & Sahinidis, 2003, Acevedo & Pistikopoulos, 1998).

To formulate planning problems within a two-stage stochastic framework depends upon grouping decision variables into ones that must be made at the present in the face of uncertainties ("*here-and-now*") and others that can be taken as corrective actions at a later stage based on the information that becomes available after uncertainties are revealed ("*wait-and-see*"). For the environmentally conscious process planning problem proposed earlier, it follows naturally that the network structural decisions related to the technology selection, capacity expansion and distribution network design are grouped as first stage, while the recourse actions can manipulate the level of raw material acquisition, production and distribution in response to scenario-specific product demands and raw material availabilities. Therefore, given a set of $k \in \mathcal{K}$ scenarios corresponding to different realizations of product demand and raw material availability, the variables are grouped as presented in Table 1.

Also, given the probability ψ^k of each scenario occurring, then the expected economic and environmental performance objectives can be expressed as the sum over the outcomes of all the scenarios (Eqs. 1 & 2, respectively). For each scenario, the expected net earnings after taxation (Eq. 3) is calculated by subtracting the distribution, raw material and production cost, and depreciable capital allowance from the product sales revenue.

Calculating the environmental performance objective requires the impact assessment of each life cycle stage whereby the contributions of the various environmental burdens to the impact categories are computed (Eq. 4). Finally, feasibility can only be ensured if the sales and purchases satisfy the scenario specific demands and availabilities (Eqs. 5 & 6).

The resulting overall formulation is the multi-objective MILP problem:

$$\min\ U\left\{\begin{array}{l} -E[f_1] = -\text{Expected Net Present Value}, \\ E[f_2] = \text{Expected Eco-Indicator 99 Score} \end{array}\right\}$$
$$st:\ x \in X \qquad \text{(P1)}$$

where U is the utility function and, for notational convenience, x represents the vector of continuous and discrete variables belonging to the feasible region of equality and inequality constraints, X.

Table 1. Two-stage stochastic model notation

First Stage Binary Variables	
Y_{jst}	1 if capacity of plant *j* at site *s* is increased during time interval *t*, 0 otherwise
X_{smt}	1 if site *s* supplies demand node *m* during time *t*, 0 otherwise
First Stage Continuous Variables	
F_{jst}	total capacity of plant *j* at *s* during interval *t*
FE_{jst}	amount by which capacity of plant *j* at *s* is expanded during *t*
CL_{jst}	installation/expansion capital investment required by plant *j* at *s* during *t*
DC_t	depreciable capital allowance allocated to time *t*
Second Stage Continuous Variables	
ET^k_t	Net earnings after taxation
P^k_{ijst}	production rate of product *I* by plant *j* at *s* during *t*
U^k_{rjst}	consumption of raw material *r* by plant *j* at site *s* during *t*
Q^k_{ismt}	flow if *i* from site *s* to market *m* during *t*
D^k_{sect}	environmental damage in terms impact category *e* resulting from life cycle stage *c* associated with site *s* during *t*
W^k_{sct}	reference flow amount of life cycle stage *c* required by production site *s* during time *t*
Uncertain Parameters	
dL^k_{imt}	lower demand of product *i* at market *m* during *t*
dU^k_{imt}	upper demand of product *i* at market *m* during *t*
a^k_{rt}	availability of raw material *r* during *t*
ψ^k	probability of scenario *k* occurring
Selected Deterministic Parameters	
ϕ	corporate discount rate
φ	corporate tax rate
τ	number of years in each time interval
υ_{imt}	unit sales price of product *i* at market *m* during *t*
	cost of transporting *i* from *s* to *m* during *t*
ω_{ismt}	unit cost of purchasing raw material *r* during *t*
ρ_{rt}	unit price of fuel oil during *t*
γ_t	fuel oil equivalent tonne (FOET) of utility
μ_{ij}	requirements for the unit production of *i* using plant *j*
δ_{eb}	characterization factor for converting burden *b* into impact category *e*
β_{cb}	emissions inventory entry for burden *b* resulting from the unit reference flow of life cycle stage *c*
η_n	normalization factor of damage category *n*
ν_n	weighting factor of damage category *n*

$$E[f_1] = \text{Expected Net Present Value}$$
$$= \sum_k \psi^k \left[\frac{\sum_t \left(ET_t^k + DC_t - \sum_j \sum_s CL_{jst} \right)}{(1-\phi)^{\tau(t-1)}} \right] \qquad (1)$$

$$E[f_2] = \text{Expected Eco-Indicator 99 Score}$$
$$= \sum_k \psi^k \left[\sum_t \sum_s \sum_n \nu_n \left(\eta_n \sum_{e \in L_{en}} D^k_{\mathrm{sec}t} \right) \right] \qquad (2)$$

$$ET_t^k = (1-\varphi)\left[\sum_m \sum_i \upsilon_{imt} \sum_s Q_{ismt}^k - \sum_m \sum_s \sum_i \omega_{ismt} Q_{ismt}^k \right.$$

$$\left. - \sum_s \sum_r \rho_{rt} Q_{rt}^k - \sum_s \sum_j \gamma_t \sum_i \mu_{ij} P_{ijst}^k - DC_t \right], \ \forall t,k \quad (3)$$

$$D_{sect}^k = W_{sct}^k \sum_b \delta_{eb} \beta_{cb}, \qquad \forall s,e,c,t,k \quad (4)$$

$$dL_{imt}^k \le \sum_s Q_{ismt}^k \le dU_{imt}^k, \qquad \forall i,m,t,k \quad (5)$$

$$Q_{rt}^k \le a_{rt}^k, \qquad \forall r,t,k \quad (6)$$

Application

Revisiting the illustrative example previously presented (Hugo & Pistikopoulos, 2003), but considering now 16 distinct scenarios of different product demands and raw material availabilities, the two stage stochastic formulation is applied. The solution to this problem is the set of robust Pareto optimal solutions that hold over all of the expected scenarios (Figure 1). Clearly a conflict exists between a network design that achieves minimum environmental damage and one that achieves maximum net present value. It shows that an improvement in the environmental performance is only possible if the decision-maker is willing to compromise the net present worth of the investment. It is also of interest to present the expected set of robust solutions together with the solutions of the best and worst scenarios. These extreme trade-off curves provide the decision-maker with the degree of confidence that can be placed in the robust investment strategy.

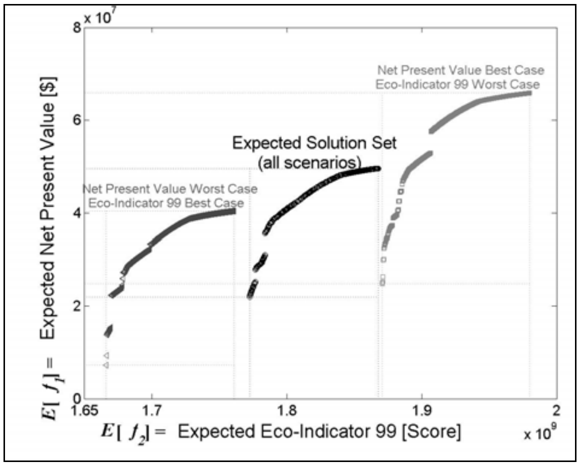

Figure 1. Expected Pareto set of solutions together with extreme scenarios

Conclusions & Future Directions

In this paper, we presented the reformulation of our deterministic model for the environmentally conscious long-range investment planning and strategic design of supply chain networks. Addressing the uncertainties in long-term market conditions as multiple scenarios, a two-stage stochastic formulation is derived giving consideration to not only the traditional economic criteria, but also to the multiple environmental concerns. With each solution in the resulting Pareto optimal set representing an alternative supply chain configuration and investment strategy that can accommodate each of the foreseen scenarios, the trade-off between the financial benefits and environmental damages can be explored. Future work will build upon the stochastic formulation to also account for the various uncertainties associated with the environmental performance quantification.

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