RISK AND TRANSIENT DEMAND IN DESIGN AND PLANNING OF SUPPLY CHAIN NETWORKS CONSIDERING ENVIRONMENTAL ASPECTS

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Abstract

This paper addresses simultaneously strategic and tactical aspects of the design and planning of multi-product supply chain networks, while accounting not only for economic but also environmental aspects under an uncertain market setting. At the strategic level the design of the supply chain network, as well as the set of technologies associated to the multi-product and multipurpose production facilities are selected. At the tactical level the planning details related to demand satisfaction are defined, considering the selected design and technologies. A two-stage stochastic mixed integer linear programming (MILP) approach is proposed taking into account a time varying demand uncertainty along pre-defined periods during the assumed planning horizon. Risk management aspects are modelled through a financial risk model incorporated into the stochastic programming formulation. Finally, a multi-objective optimization approach is developed to establish the trade-off between profit, risk and environmental impacts. The effectiveness of the proposed approach is shown through the solution of an illustrative example.

Keywords

Financial Risk, Uncertainty, Life Cycle Analysis, Multi-objective Approach.

Introduction

Nowadays with the increased market competition becomes essential to deal with efficient integrated supply chain (SC) networks. Worldwide business led to the availability of sets of alternative resources as well as to a vast array of potential customers, justifying the present need for efficient management of supply chains. Customers' changing expectations regarding the value of goods and services, combined with advances in technology and the fast access to information, have driven to the creation of inter organizational networks with the aim to minimize the uncertainty associated. To achieve such level of coordination several aspects must be contemplated at the SC design and planning level. Not only the interaction between all the entities must be taken into account when designing the networks, but also the optimal planning of the involved resources must be accounted for (Papageorgiou, 2009). Uncertainty of market demand needs also to be considered (Grossmann, 2004). Within this context it is required an integrated model where strategic and tactical decisions are taken into account simultaneously, while accounting for markets uncertainty.

In spite of a considerable amount of research that has already been carried out on supply chain management (Papageorgiou 2009), the integration of economic uncertainty with financial risk requires further work.

In (2003), Bagajewicz and Barbado discussed a theoretical development related to financial risk management in the framework of a two-stage stochastic programming for planning under uncertainty. Few years later, Azaron *et al.* (2008) developed a multi-objective programming

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approach for supply chain design under uncertainty. The model includes de minimization of the sum of current investment and expected capacity costs; the minimization of the variance of the total cost and minimization of financial risk. The work presented by Mitra *et al.*, (2008) addressed uncertainty issues, related to production demands, machine uptime and various cost components, by using a fuzzy approach that led to the evaluation of multi-objective Pareto trade-offs among the total cost of planning model, margin provided in the constraints violation and the extent of demand satisfaction. You *et al.* (2009) presented a risk management approach for mid-term planning of a global multi-product chemical supply chain under demand and freight rate uncertainty. A two-stage stochastic linear programming approach proposed within a multi-period planning model that takes into account the production and inventory levels, transportation modes, time of shipments and customer service levels. More recently, Mula *et al.* (2010) proved the effectiveness of a fuzzy mathematical programming approach to model a supply chain production problem with demand uncertainty. In (2011) Corsano and Montagan proposed a new approach where decisions about plant design are simultaneously made with operational and planning decisions in the supply chain. The model considers unit duplication and allocation of storage tanks. Georgiadis *et al.* (2011), consider a detailed mathematical formulation for designing supply chain networks, comprehending multiproduct facilities with shared production resources, warehouses and distribution centers operating under time varying demand uncertainty.

Furthermore, the handling of environmental aspects together with risk and uncertainty remains an area of research.

Bojarski *et al.* (2009) addressed the optimization of the design and planning of supply chains considering economic and environmental issues. The IMPACT 2002+ methodology was selected to perform the impact assessment. Guillen-Gosalbez *et al.* (2009) also studied the design and planning of supply chains. A MINLP bi-objective stochastic formulation that accounts simultaneously for the maximization of the net present value and the minimization of the environmental impact was considered. The Eco-indicator 99 was explored to model environmental aspects. Later on, Guillen-Gosalbez *et al.* (2010) studied again the same problem to improve the solution efficiency and developed a spatial branch and bound method that guarantees global optimality of the Pareto solutions found.

Pinto-Varela *et al.* (2011) also addressed the planning and design of supply chain structures for annual profit maximization, while considering environmental aspects. Profit and environmental impacts are balanced through the use of an optimization approach adapted from symmetric fuzzy linear programming (SFLP), while the supply chain is modelled as a mixed integer linear programming (MILP) optimization problem using the Resource-Task-Network methodology.

Despite the fact that some work has already been presented, there is still the need to develop alternative formulations for the design and planning of SC while accounting simultaneously to risk, uncertainty and environmental aspects.

The present work deals with this problem and develops a detailed mathematical programming for the design and planning of a multi-stage supply chain, considering multi-product and multipurpose facilities while modeling environmental, uncertainty and risk aspects. The Resource-Task-Network model presented by Pinto *et al.* (2011) is taken as a basis.

As the problem complexity increases, more aspects become necessary to integrate and the fact that we are dealing with several conflicting objectives, with varying importance for the decision-maker, leads to the use of a multi-objective approach. By this fact a pre-emptive optimization is used. This performs a multi-objective optimization by considering objectives one at a time: the most important is optimized, then the second, subject to the requirement that the first achieved its optimum value, and so on. The potential of the presented approach is highlighted through an illustrative example.

The organization of this paper is as follows. Next the problem characterization is presented, followed by the model framework and an example illustration. Finally, some conclusions are drawn.

Problem Statement

The SC includes a set of manufacturing sites that are multipurpose in nature, implying that more than one product can be produced while sharing the available resources. The network comprises several manufacturing sites or facilities, which are selected from a set of potential locations, employing technologies and warehouses, as well as various distribution centers located also at a pre-selected set of potential locations. The strategic decision involves the choice of facilities, warehouses, distribution centers locations and technologies. From a tactical point of view the capacities of facilities, warehouses and distribution centers are obtained, together with the planning details of the resources involved to satisfy market demand. Not only the material storage handling capacities of warehouses and distribution centers are limited within certain bounds, but also the set of technologies' resources. From the operational level and using a discrete time horizon, the model defines in which instant of time each technology occurs, characterizing the schedule for each facility. The inventory profile is obtained along the horizon as well as the production tasks and distribution flows.

The environmental issues consider the impacts generated by electricity and diesel consumption in the SC not only at the strategic but also the operational level. A set of instants of time are defined as a period. The discrete time horizon used in the paper is characterized by two periods. A nominal demand and destination market for each product are associated for each period. Each period is also characterized by the occurrence of alternative scenarios used in the stochastic two-stage approach. A scenario is represented by a discrete probability function. The problem in study can be summarized as follows**.**

Given: discretization of a fixed time horizon; a set of products; a set of markets in which products are available to customers and their nominal demand; a set of geographical sites for locating resources: production, storage and distribution; a set of technological processes for product manufacturing; lower and upper bounds for the capacity of the technological resources; the RTN representation for the product transformation along the chain; suppliers capacity; fixed and variable costs associated to the setting up of the technological resources; fixed and variable costs associated to materials transportation; fixed and variable operational costs; price for every product in each market and raw-material costs; a set of scenarios and their probability of occurrence; the demand associated at the end of each period; diesel and electricity consumptions; all the necessary environmental specifications and parameters.

Determine: the technological resources to be installed and their capacities; the supply chain topology (facilities, warehouses and distribution centers); the technological resource scheduling for each facility; the amount of final products to be sold in different markets at each period; the inventory profile and the flow of materials to be transported.

So as to maximize the supply chain profit, while simultaneously minimizing the environmental impact and the financial risk.

Model Framework

RTN Supply Chain Network Design and Planning

The Resource-Task-Network (RTN), presented by Pantelides (1994), is a general and conceptually simple representation methodology. Its main feature resides in the use of two concepts: tasks and resources. A task in a supply chain context represents a technological process that, for example, might involve different processing or multipurpose storage operations associated with a warehouse or distribution centre. Therefore a certain technological resource can support various technological processes, which will be denoted simply by tasks (i.e. a set of operations that describe a production process of a product). Resources can be classified as non-renewable, which represent all kinds of materials, utilities, manpower, etc., and renewable, which represents all types of technological resources, associated to the supply chain network, i.e. multipurpose production lines with their equipments, warehouses, distribution centers, transportation resources, etc. The technological resources, to be referred simply as technologies, are specified not only in terms of design characteristics (i.e. capacity) but also in terms of localization, thus allowing for the establishment of distances between entities. Such distances are then associated with the transportation resources that will guarantee the transfer of materials along the network allowing an explicit description of the physical supply chain network.

Environmental Aspects

LCA can be described as a quantitative framework for considering the environmental impacts associated with every stage in the life cycle of a product, from raw materials production to final disposal. Based on this, the Eco-indicator methodology appears as a powerful tool for designers to aggregate LCA results into easily understandable and user-friendly quantitative units (Ministry of Housing et al. 2000). The Eco-indicator 99 introduces a damage function approach that represents the relation between the impact and the damage to human health, resource and ecosystem. Such methodology involves three main steps: (1) inventory of all relevant emissions, resource extractions and land-use in all processes that form the life cycle of a product, (2) calculation of the damages that these emission flows cause on Human Health, Ecosystem Quality and Resources and (3) weighing these damage categories. Based in Pinto-Varela (2011) work, the Eco-Indicator methodology is used along this paper to model the environmental aspects within the design and planning of SC.

Uncertainty

The stochastic approach that will be followed is based on a two-stage linear model, which involves a combination of wait-and-see and here-and-now decisions. The decision variables are split in two major groups: first- and second-stage. Variables for the first-stage are those related to decisions that cannot be reviewed, or which are less prone to be modified, once the future outcomes are realized, characterizing the here-and-now decision. Within the present model, these are the design variables, selecting: a set of facility, technologies, warehouses, distribution centers, etc. The second-stage variables are related with decisions that can be reviewed after the scenario occurrence (i.e. additional information is obtained on the realization of some random vector), defining the wait-and-see decisions. In our model, those are the planning variables, characterized by the batches associated to the selected technologies', materials flows and facilities, distribution centers and technologies capacities decisions.

In the two-stage model characterization two scenarios are implemented, optimistic and pessimistic, along the entire horizon. However some considerations are taken based in the fact that the decision maker is able to exploit the forecasting data to define a more accurate products demand in the first period, where the uncertainty became less relevant. In the first period it is assumed that the demand is equal in both scenarios, for each product, allowing the model to treat the continuous variables as only a single scenario. At the end of the first period the product demand becomes available for the following period, resulting in a two scenarios branching, where the demand is differentiated for each productin each scenario, shown in Figure 1 (Georgiadis et al. 2011).

The two-stage linear model with recourse formulation is defined as equations (1) and (2). Consider M as the set of all possible scenarios and $m \in M$ a particular scenario. Let all first-stage variables be included in vector y and all second-stage variables in vector x. Let f be the vector of the fixed coefficients related to the choice of a certain resource c and p the vector containing the remaining coefficients in the objective function. A_m, B_m and p_m, c_m are matrixes and a_m is a vector.

The two-stage stochastic linear model with recourse becomes:

$$\begin{aligned} \max \quad & E[profit] = E\left[\Theta(y,m)\right] - fy \\ s.t. \quad & y \in \{0,1\} \end{aligned} \tag{1}$$

with,

$$\begin{aligned} \max \quad & \Theta(y,m) = p_m x_m - c_m x_m \\ s.t. \quad & A_m x_m \le a_m \\ & B_m x_m \le Cy \\ & x_m \ge 0, x_m \in R \end{aligned} \tag{2}$$

Where $E[.]$ is the expected value of $[.]$ over *m,* and p_m, c_m are associated with the distribution function J_m.

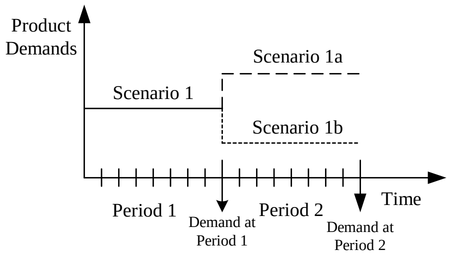

Figure 1 – Uncertainty representation.

Financial Risk

The design of a supply chain under uncertainty requires the integration of the financial risk. The financial risk is defined as the probability of not reaching a certain goal, which may be an economic index (e.g. profit or cost) characterized as Ω. Using the goal of Ω associated with the cost, the risk of a supply chain design can be defined as the probability of the cost being greater than the goal Ω. This approach characterized by the constraint (3) (You et al. 2009), aims at the reduction of the financial risk and through minimization of the costs.

$$Risk(x,\Omega) = \Pr[Cost(x) \ge \Omega] = \sum_{m \in M} p_m z_m \tag{3}$$

For the scenario planning model a binary z_m, is introduced such that z_m equal to 1 if $Cost_m \ge \Omega$, otherwise is equal to 0. To define the binary variable (Barbaro et al. 2004) proposed the following Big-M constraints:

$$Cost_m \le \Omega + M\, z_m \tag{4}$$

$$Cost_m \ge \Omega - M\,(1 - z_m) \tag{5}$$

Multi-objective approach

In this paper the multi-objective model is reduce to a sequence of single objective optimizations using the lexicographic optimization (Rardin 2000). This approach takes the objective function in importance order. The most important is the profit maximization, followed by the environmental impacts and finally the risk minimization. The first model to be solved uses the profit maximization. Assuming the obtained value for the profit, an extra constraint is added to the model to keep the profit value satisfied. A second model is formulated using the financial risk minimization as the objective functions and another solution is obtained. The procedure goes on, until all the objective functions are satisfied. This approach requires the improvement of each objective function without worsening the others. When the procedure is finished, no further improvement is possible.

Example

An illustrative example based on a Portuguese SC network to be designed and produce six types of final products (P4, P5, P6, P7, P8 and P9) is considered. Five potential locations are assumed for the industrial facilities (sites A, B, C, D and E). The SC presents one non-storable intermediate material (P3) and three materials (P4, P5 and P8), which are simultaneously intermediate and final products. Multipurpose facilities are assumed, meaning that each facility may process different products using a number of shared resources and technologies, Table 1. Warehouses, which also act as distribution centers (DC), are dedicated to one product and the respective potential location is near the consumers (market). The DCs capacities are obtained taking into account the demand for each market. The product demand fluctuates along the time horizon. A two period time horizon was considered with a discretization time of 12 for each period. Table 2 presents the demand for each product, scenario and period. The demand uncertainty is considered as a set of two scenarios, each one associated with an occurrence of 0.8 and 0.2 (optimistic and pessimistic scenarios, respectively).

The suppliers' localization is fixed. The transportation costs are dependent on the geographical distance between the locations involved and quantities transported. Full truck load freights at an average speed of 80 km/h are assumed. In terms of environment, it is assumed that for each technological resource, some electricity consumption will occur together with an associated environmental impact. Also other environmental impacts, i.e. those related to transportation namely in terms of CO_2, NO_x and SO_x emissions, will be considered. The data from the pollutants emitted per utility consumption is defined in (Duque et al. 2010), and the damage to human health factors in (Geodkoop et al. 2001).

Table 1. Facilities suitability and final products.

Potential sites	Technology	Final Products
Site A and B	T1, T2, T5	P7, P4
Site C and D	T1, T2	P4
Site E	T3, T4	P5,P6,P8,P9

Table 2. Demand and market characterization.

Product	Market	Scenarios	Period 1 [tonnes]	Period 2 [tonnes]
P4	DC_Lisbon	Optimistic	280	420e2
		Pessimistic	280	560
P5	DC_Lisbon	Optimistic	580	720e2
		Pessimistic	580	1160
P6	DC_Lisbon	Optimistic	460	600e2
		Pessimistic	460	920
P7	DC_Porto	Optimistic	450	590e2
		Pessimistic	450	900
P8	DC_Faro	Optimistic	200	340e2
		Pessimistic	200	400
P9	DC_Faro	Optimistic	260	400e2
		Pessimistic	260	520

In this work, we aim to maximize profit, while minimizing risk and environmental impacts taking into account all scenarios and the transient demand. To do so, a lexicographic optimization is used, which performs a multi-objective optimization by considering objectives ordered by level of importance, where profit is the most important, followed in turn by risk and environmental impact.

The obtained results are shown in tables 3 to 5 and the supply chain network is characterized in Figure 2. It can be seen that facilities are opened in four locations (Sites A, B, C and E), Table 3. In site A, technology T2 is selected to produce P4; site B facility only uses technology T5 for P7 production; site C facility produces the instable product P3, using technology T1; finally, site E facility produces P5, P6, P8 and P9 with technologies T3 and T4. The supply chain network is shown in Figure 2. Table 4 shows the distribution centers design (i.e. capacity) for each product, followed by the production for each product, in each scenario and period, in Table 5. Comparing the results of production in Table 5 with Table 2, it can be seen that P4 production is only satisfied in the second period. This results from P4 being also an intermediate product. However, the demand in the first period is satisfied for the remaining products. In the second period only the demand associated to the optimistic scenario of products P6, P7 and P9 are not fully satisfied. This supply chain design and planning presents a cost which exceeds the budget value (1E11monetary units), resulting in quite a high risk value (0.8).

The model applied required 11644 constraints and 1775 discrete variables in a total of 7043 variables. The optimal profit, risk and Eco-indicator 99 values are 1.277E11 monetary units, a risk value of 0.8 and 2.44E5 mPt, respectively.

Table 3. Facilities sites design, selected technology and products produced in each facility.

Sites	Technology	Final Products	Design [tonnes]
Site A	T2	P4	12 917.5
Site B	T5, T2	P7	4 856.6
Site C	T1	P3	13 197.5
Site E	T3, T4	P5,P6,P8,P9	26 395

Table 4. Warehouse/ DC design.

Market	Products	DC_Design [tonnes]
DC_Lisbon	P4	42 000
DC_Lisbon	P5	72 000
DC_Lisbon	P6	920
DC_Porto	P7	58 729
DC_Faro	P8	34 000
DC_Faro	P9	520

Table 5. Production at the end of each period.

Products	Scenarios	Period 1 [tonnes]	Period 2 [tonnes]
P4	Optimistic	-	420e2
	Pessimistic	-	560
P5	Optimistic	580	720e2
	Pessimistic	580	1160
P6	Optimistic	460	920
	Pessimistic	460	920
P7	Optimistic	450	58 729
	Pessimistic	450	900
P8	Optimistic	200	340e2
	Pessimistic	200	400
P9	Optimistic	260	520
	Pessimistic	260	520

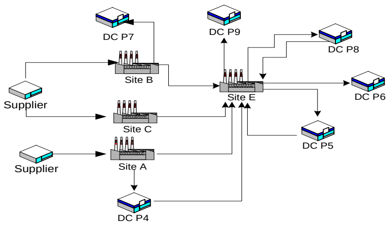

Figure 2 – Supply Chain Network.

Conclusion

In this paper the detailed design and planning of a supply chain network are optimized taking simultaneously into account economic, financial risk and environmental aspects, and assuming an uncertainty market characterized by a floating demand. The proposed model allows the selection of different entities commonly present in a generic supply chain such as: production facilities, warehouses and distribution centers. In addition, for all site locations the types of technological resources used, which may be multipurpose in nature, are also determined, hence allowing for the production of different products while sharing installed resources.

This problem is multi-objective in nature and was tackled in this work by a lexicographic approach, where profit maximization, risk and environmental impact minimization, are considered. The mathematical formulations incorporate three methodologies: the Resource-Task-Network used to define the supply chain characteristics with no ambiguity; the Eco-Indicator 99 that quantifies the environmental aspects; and a two-stage stochastic approach. This model is currently being applied to real supply chains in order to be better validated and generalized.

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