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Supply Chain Network Optimization with Environmental Impacts

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Abstract

Traditionally the design of supply chains has been based on economic objectives. As societal environment concerns grow, environmental aspects are also emerging, at the industry level, as decisive factors within the context of supply chain management. The investment towards logistics structures that consider both economic and environmental performance is nowadays an important research topic. However, much is still to be done.

This paper, addresses the planning and design of supply chain structures for annual profit maximization, while considering environmental aspects. The latter are accounted through the Eco-indicator methodology, which is used to quantify the damage to human health. 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 (RTN) methodology. The obtained model is validated through the solution of an example, where its applicability to supply chain problems is demonstrated.

Keywords: Planning, Design, Fuzzy, Multipurpose, Environment, RTN.

1. Introduction

Sustainable Supply Chains can be seen as logistic structures that guarantee the production and distribution of products globally in an environmental friendly manner [1]. To achieve such goal, companies must invest on the design and planning optimization of their logistic structures, while accounting for the trade-off between profits and environment impacts.

In spite of a considerable amount of research having already been carried out on supply chain management, a new area exploring environmental aspects is now emerging.

In recent years there has been a growing awareness for the importance of incorporating environments aspects along with the traditional economic indicators. This trend has been motivated by several issues, a major one being tighter governments regulations and customers' perception towards more environmentally conscious systems, which may eventually lead to higher product sales [2].

Hugo *et al.* [3] presented a combination of life cycle criteria for the design and planning of multi-enterprise supply chain networks. By the same authors, a multi-objective optimisation approach for hydrogen networks is described, where the trade-offs between investment and greenhouse gas emissions is investigated [4]. More recently, work has been published on Closed -Loop Supply Chains, where forward and reverse flows are taken into account simultaneously [5].

Melo et al. [6] presented a survey, where the majority of cited papers feature a cost minimization objective and noticed that very few articles refer to models subject to multiple and conflicting objectives, which cover both profit and environmental aspects.

In this work and using a generic and uniform mathematical framework, i.e. the Resource-Task-Network (RTN), the optimal design and planning of a supply chain is investigated by means of a bi-objective formulation, where profit maximization is addressed together with minimization of environmental impacts.

The resolution of such formulation may become very lengthy with an increase in the problem dimension and complexity. For this reason, we adopt an alternative optimization approach, based on symmetric fuzzy linear programming (SFLP), which uses one single new objective criterion, which embodies a compromise between the initial conflicting objectives.

The paper is structured along five sections. Section 1, the current one, gives an introduction to the work. In section 2 the model framework is characterized, i.e. the Resource-Task-Network Methodology is presented and explained, together with the main concepts associated with the life cycle assessment, followed by an introduction to the fuzzy approach applied to the model. Section 3 presents the problem formulation and section 4 illustrates the model applicability. This paper concludes with final remarks and lines for future work.

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2. Modelling framework

As stated above, the current problem uses three main methodologies, the Resource-Task-Network, the Life Cycle Assessment and the Fuzzy-Like Approach. The first is related to the definition of the supply chain activities and structure, while the second accounts for the modeling of the environmental aspects that are considered in the problem and, finally, the third deals with a balance between the conflicting objectives, i.e. maximization of profit and minimization of environmental impacts.

2.1. Resource-Task-Network Methodology

The Resource-Task-Network (RTN), presented by Pantelides [7], is a general and conceptually simple representation methodology. Its main characteristic lies in the uniform description and characterization of the available resources, with no distinction between them, and on the definition of tasks. A Task is an abstract operation that consumes and/or produces a specific set of Resources. Resources can be classified in: non renewable, which represents raw materials, utilities, manpower, etc., and renewable, which represents all types of equipment associated to the supply chain network (manufacturing, warehouse, distribution center, transportation, etc). The classification of the available Resources into the smallest possible number of distinct types depends on the detail of the modelling employed (their functional equivalence). Thus, the set of attributes, which may or not characterise a Resource type, is context dependent. The interaction between Tasks and Resources leads to the Resource-Task-Network, which is a bipartite directed graph [8]. Using such representation the supply chain resources (materials, plants, transportation network and resources) and tasks (activities: produce, transport, store, supply...) are modelled generating an optimization model, where all the supply chain design characteristics are integrated.

2.2. Life Cycle Assessment Approach

The environmental science and engineering community have developed several systematic methodologies for the detailed characterization of the environmental impacts of products and processes. All of these methodologies have embodied the concepts of life cycle, i.e. they are based on a Life Cycle Analysis, which is well described in ISO documents (ISO14040, 1997). This is a framework that considers the entire life cycle of the product, process or activity, encompassing extraction and processing of raw materials; manufacturing, transport and distribution; re-use, maintenance recycling and final disposal [9].

Life-cycle analysis (also referred to as life-cycle assessment) can thus be described as a quantitative framework for considering the environmental impacts associated with every stage in the life cycle of a product (essentially based around mass and energy balances, but applied to a complete economic system rather to than a single process), from raw materials production to final disposal. The complexity of the decision process involving all environmental aspects means very often an unbridgeable gap for the researchers. Life cycle assessment (LCA) is a good tool to assess the environmental performance of a product but while widely used by designers it is time consuming and costly. The Eco-indicator methodology is an LCA weighing method, which has proved to be a powerful tool for designers to aggregate LCA results into easily understandable and user-friendly quantitative units. The Eco-indicator 99 introduces a damage function approach that represents the relation between the impact and the damage to human health or to the ecosystem [10].

The Eco-indicator 99 methodology requires three steps:
-   Inventory of all relevant emissions, resource extractions and land-use in all processes that form the life cycle of a product.
-   Calculation of the damages these emission flows cause to the Human Health, Ecosystem Quality and Resources.
-   Weighting of these damage categories.

In this work, we will employ a carbon footprint approach in the application of the quantitative methodology Eco-indicator 99, where only damage to human health caused by electricity and diesel consumption over the entire supply chain is considered.

2.3. Symmetric Fuzzy Linear Programming

The approach applied borrows the concept of degree of feasibility from a fuzzy approach that makes use of Zimmermann's [11] symmetric fuzzy linear programming (SFLP) method. Constraints are made flexible with the introduction of the concept of degree of feasibility, thus allowing multiple objective functions to be treated as fuzzy constraints and reducing the optimization problem to the maximization of the degree of feasibility of all

objectives simultaneously. The key features of SFLP are [12]: (1) Crisp or non-fuzzy constraints are converted into fuzzy constraints by introducing tolerances. These modifications introduce the concept of degree of satisfaction of a constraint bounded to the interval [0, 1]; (2) An aspiration level is identified for each objective function, such that optimization entails maximizing the degree to which the objective is satisfied. This step involves identifying the best and worst values for each objective. The degree to which an objective is satisfied is also bounded to the interval [0, 1].

Objectives and constraints are treated in the same manner in SLPF, hence the use of the term symmetric. A new variable, λ, is introduced in the model serving to simultaneously modulate the degree of satisfaction of all the constraints or objectives. The SFLP is then formulated to maximize λ, which in effect expresses the global degree of satisfaction of the model [12].

We now assume that the decision maker can establish an aspiration level, z, to be achieved for each objective function. This methodology can be generalized for optimization problems with several objectives. The objective functions are then modeled as fuzzy sets and the crisp constraints added to the formulation. The fuzzy model can be formulated as:

$$\max \lambda \tag{1}$$

$$\sum_i a_i x_i \leq z_1^U - \lambda(z_1^U - z_1^L) \tag{2}$$

$$\sum_i b_i x_i \geq z_2^L + \lambda(z_2^U - z_2^L) \tag{3}$$

$$g_j(x) \leq 0 \qquad j = 1, 2, \ldots J; \tag{4}$$

$$h_k(x) = 0 \qquad k = 1, 2, \ldots, K; \tag{5}$$

$$0 \leq \lambda \leq 1 \tag{6}$$

Where λ defines the index of constraints satisfaction, z_1^U and z_1^L, define respectively the upper and lower bound of the environmental impact objective function, z_2^U and z_2^L define respectively the upper and lower bound of the profit objective function.

In the model with respect to the environmental impact, Eq. (2), the z_1^U gives the highest impact level (worst case), and z_1^U - z_1^L gives the variation range, defining the fuzzy interval. When $\lambda = 0$ the impact is given by z_1^U and for $\lambda = 1$ the impact is at its lowest and defined by z_1^L. As the degree of satisfaction increases, the environmental impact reduces.

The Eq. (3) defines the fuzzy intervals for the profit objective function. This objective is concurrent to the environmental impact objective. When $\lambda = 0$ the profit is defined by the lower bound, z_2^L and when $\lambda = 1$ the upper bound defines the maximum profit.

The variable λ serves to modulate the objectives, where each objective must be satisfied up to a degree of at least λ.Thus, maximizing this variable effectively pushes the model towards the best compromised solution. The relative importance of the various objectives can be reflected in the model through a careful choice of the upper and lower bounds values.

3. Problem Statement

A supply chain design is going to be optimized while considering not only economic aspects but also environmental issues. The supply chain includes a set of manufacturing sites that are multipurpose in nature, meaning 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 from a pre-selected set, and one warehouse and various distribution centres located also at a pre-selected set of potential locations. A strategic decision involves the choice of facilities, warehouse and distributions centres locations, as well as of technologies. From a tactical point of view the capacities of facilities, warehouse and distribution centres are obtained, as well as the materials flows associated with the network. Each warehouse may be supplied from more than one manufacturing site. The material storage handling capacities of warehouses and distribution centres are limited within certain bounds.

As already stated, environmental issues are simplified considering only impacts generated by electricity and diesel consumption over the entire supply chain.

Summarising and assuming a uniform discretization of time, the problem in study can be stated as follows:

Given:
- 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 facilities, warehouse and distribution centres;
- a set of technologies for product manufacturing;
- lower and upper bounds for the capacity of facilities, warehouse and distribution centres;
- the RTN representation for the product recipes;
- suppliers capacity;
- fixed and variable costs associated to the setting up of facilities, warehouse and distribution centres;
- fixed and variable costs associated to materials transportation;
- fixed and variable operational costs;
- price for every product in each market and raw-material costs;
- diesel and electricity consumptions;
- all the necessary environmental specifications and parameters.

Determine:
- the facilities to be opened;
- the technology to be selected;
- the facility, warehouse and distributions centres design;
- the amount of final products to be sold in different markets;
- the flow of materials to be transported.

So as to balance the maximization of the supply chain profit, while simultaneously considering the environmental impact minimization

4. Illustrative Example

To illustrate the methodology applicability, a Portuguese supply chain network producing four final products (S4, S5, S6 and S7) is to be designed. Five potential locations are considered for the industrial facilities. The supply chain presents one non-storable intermediate material (S3) and two intermediate materials (S4, S5), which are simultaneously intermediate and final products. Multipurpose facilities are assumed, which means that each facility may process different products using a number of shared resources and technologies (Table 1). Each warehouse, which acts also as a distribution centre (DC) is dedicated to one product and the respective potential location is near the consumers (market). The DCs capacities are obtained taking into account the maximum and minimum demand for each market (Table 2). The supplier's localization is fixed in Aveiro and Beja. In Figure 1 is shown the potential locations for all entities in Portugal (districts) that characterize the supply chain.

Fixed and variable costs associated with different warehouse/distribution centres are similar, with the same applying to different facilities. However, the facility with potential location near the Spanish border has a decrease in the fixed cost of 50%, due to the social and economical environmental characteristics of this region.

The transportation costs are dependent on the geographical distance between the locations involved and quantities transported. It was assumed full truck load freights and an average speed of 80 km/h.

Table 1– Facilities suitability and final products production.

Facilities	Technology	Products			
Potential sites	Potential set	Storable	Non Storable	Intermediate	Final
Guarda	T5, T2, T1	S7, S4	S3	S3, S4	S7, S4
Vila Real	T5, T2, T1	S7, S4	S3	S3, S4	S7, S4
Castelo Branco	T2, T1	S4	S3	S3, S4	S4
Santarém	T2, T1	S4	S3	S3, S4	S4
Évora	T3, T4	S5, S6		S5	S5, S6

Table 2 – Annual range product demand for each market.

Product	Market	Demand (min :max tonnes)
S7	Porto	450:450
S4	Santarém	200:280
S5	Lisboa	500:580
S5	Faro	200:200
S6	Lisboa	400:460
S6	Faro	200:260

Figure 1- Supplier, facilities and warehouse/distribution centres potential locations.

In terms of environment, it is assumed that at each facility, some electricity consumption will occur and an associated environmental impact will exist. Also environmental impacts related to transportation namely in terms of CO_2, NO_x and SO_x emissions will be considered. The corresponding values per unit are given in Table 3.

Table 3- Pollutants emitted per utility consumption [13].

Utility	CO	CO2	NOx	SOx	Units
Diesel	14.828	2609.5	34.6	-	Kg/m^3
Eletricity	4.151e-3	7.306e-1	1.941e-3	3.872e-3	kg/kwh

As referred above the Eco-indicator 99 is used to evaluate damages on the basis of three contexts: Ecosystem, Resources and Human Health. To obtain a single indicator, a set of weights is used, usually noted by Pt (it reads Points), from the contributions of all types of damage. Those weights result from a social study (performed by the authors of the Eco-indicator 99) measuring social sensibility to each type of damage for population samples representative of three cultural perspectives: equalitarian, hierarchical and individualistic. Furthermore, due to the small dimension of the social panel used in that particular study, all subsequent work uses a set of mean weights, i.e. 40% for both Human Health and Ecosystem, with the remaining 20% assigned to Resources.

Results are normally presented in milli-Points (mPt) and thus the weighting factors used are, respectively, 400, 400, and 200[13].

This work focus on the Human Health (HH) damage and Table 4 presents the damage to human health reflecting the respiratory effects of the inorganic substances emitted by the utilities consumption. The damages to HH are expressed as DALY (Disability Adjusted Life Years). In this analysis, the hierarchical cultural perspective is used.

Table 4- Damage to Human Health [14].

Damage	CO	CO2	NOx	SOx
Human Health (DALYs/kg emission)	-	7.5e-4	8.74e-5	5.35e-5

The model was applied to the above described supply chain network and required 2861 constrains, 477 discrete variables in a total of 1849 variables. The optimal profit and Eco-indicator 99 values at the fuzzy point are 8.59E9 monetary units and 3314 mPt, respectively. The optimum solution was reached in 18 CPU seconds, with a fuzzy degree of satisfaction of 0.58

The obtained results are shown in Figure 2. It is possible to visualize that facilities were opened in three locations (Guarda, Castelo Branco and Évora). In Guarda the T5 and T2 technologies were selected to produce S7, S3 and S4. The Castelo Branco facility only utilizes T1 technology for producing S4 and S3 and finally Évora installed technologies T3 and T4 and produces the S5 and S6 products (Table 5).

Figure 2- Final supply chain network.

Both Guarda and Castelo Branco facilities receives raw materials from both suppliers (Aveiro and Beja). The product S7, with destination to Porto market is produced only in the Guarda facility. In addition, this facility also produces S3 (non-storable) to be consumed in the Évora facility and some of the final product S4 is sent to the Santarem warehouse. The product S4 is also produced by the Castelo Branco facility, which is subsequently consumed by the Évora facility to satisfy Lisbon and Faro market demand for S5 and S6 (Table 5).

Table 5 – Facilities sites and design, selected technology and products produced in each facility.

Facilities sites	Techology selected	Products produced	Facility design (tonnes)
Guarda	T5, T2	S7, S3, S4	410
Castelo Branco	T1	S4, S3	302
Evora	T3, T4	S5, S6	605

The warehouse/distribution centres design and the final products productions are presented in Table 6.

Table 6- Warehouse/ DC design and production at the end of the horizon (year).

Market	Warehouse/DC design (tonnes)	Product	Production (tonnes)
Porto	450	S7	450
Santarem	410	S4	280
Lisboa	580	S5	580
Faro	200	S5	200
Lisboa	405	S6	405
Faro	200	S6	200

Comparing the demand for all products (Table 2) and the production at the final horizon (Table 6), it is possible to conclude that the supply chain design is able to satisfy the whole of Lisbon and Faro market demand for products S7, S4, S5, while the production of S6 will miss to meet that goal.

For this supply chain the pollutants quantity resulting from the utility consumption (electricity and diesel) is shown in Figure 3. Analysing Figure 3 is possible to see that the CO_2 is the pollutant emitted in higher quantities from both utilities consumption (diesel and electricity) with electricity being the utility that presents a higher CO_2 emission.
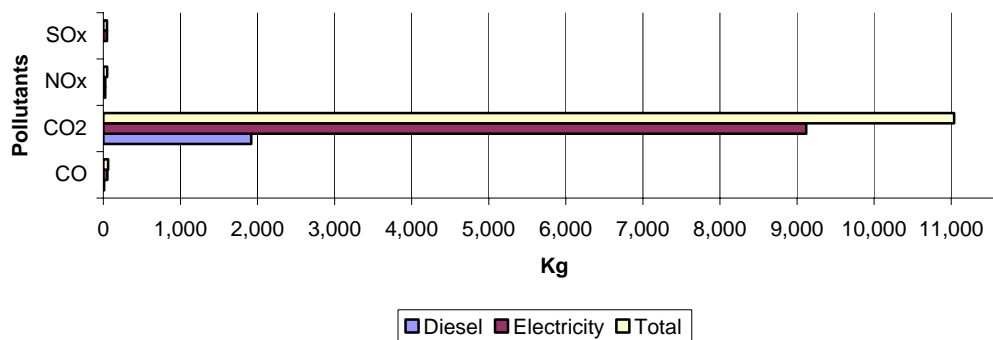

Figure 3 – Supply chain pollutants emitted from utilities.

In terms of production (Figure 4), S4 is produced first and at the beginning of the planning time, but the production level decreases along the following time intervals, reflecting the fact that S4 is simultaneously final product and intermediate material; product S6 for Faro and Lisbon markets is available from instant 8 onwards; S5 is available for the Lisbon market between instants 6 and 11, while for the Faro market production is available from instant 11 onwards; S7 for the Porto market is available as from instant 6.
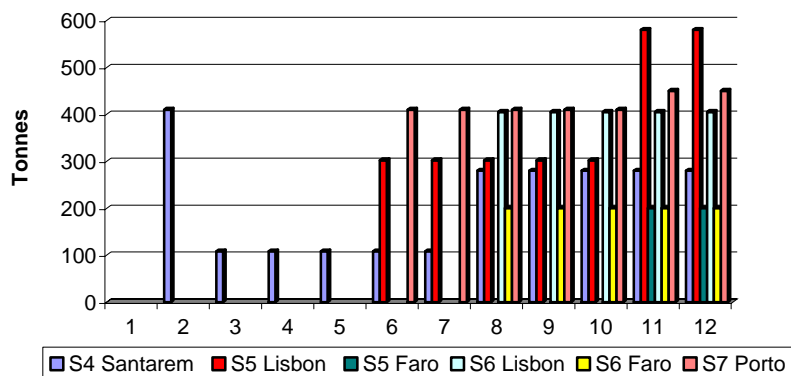
Figure 4 – Production planning.

5. Final Remarks

In this paper the supply chain network design and planning are optimized simultaneously taking into account both economic and environmental aspects, leading to the selection of the various entities (facilities, warehouse and distribution centres) which participate in the optimal configuration of the supply-chain. For all of them locations sites are also determined, as well as the type of technology used. This supply chain optimization is in practice a bi-objective optimization problem: profit maximization and environmental impact minimization. The mathematical formulations incorporate two methodologies, namely the Resource-Task-Network used to define the supply chain characteristics with no ambiguity and the Eco-Indicator 99, which quantifies the environmental aspects.

A fuzzy-like optimization approach is applied to the bi-objective problem considered, which is shown to be very efficient and provide an optimal solution that embodies a compromise between the two conflicting objectives. From a mere operational standpoint, this fuzzy-like approach can also be useful to reveal, at the preliminary optimization stages, the existence of viable optimal solutions within the preset bounds. The proposed approach can be expected to become increasingly effective as the number of simultaneous objectives increases, a line of work being currently under investigation.

The current model will be also applied to other types of supply chains in order to be better validated and generalized.

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