18th European Symposium on Computer Aided Process Engineering – ESCAPE 18
Bertrand Braunschweig and Xavier Joulia (Editors)

An Optimization Model for the Design of Closed Loop Supply Chains with Minimum Environmental Impacts

Ana Diniz Cunha,[a] Maria Isabel Gomes Salema,[c] Ana Paula Barbosa-Povoa,[b] Augusto Q. Novais[a]

[a] *DMS-INETI, Az. dos Lameiros, 1649-038 Lisboa, Portugal*
[b] *CEG-IST, Av. Rovisco Pais, 1049-001 Lisboa, Portugal*
[c] *CMA, FCT-UNL, Monte da Caparica, 2829-516 Caparica, Portugal*

Abstract

In this work, the design of supply chains with reverse flows is studied in a multi-objective context. A MILP model is developed for the optimization of the supply chain structures where both environmental impacts and costs are considered. An optimal Pareto front is obtained that plays an important role in evaluating the best locations of all the entities in the supply chain while accounting for the global supply chain environmental impacts. A study based on a Portuguese glass industry is presented to corroborate both the applicability and the adequacy of the model.

Keywords: Closed-loop supply chains, Design, Life Cycle Assessment, Multi-objective optimization

1. Introduction

Nowadays modern society is highly concerned with various environmental issues. With regards industrial activity, both customers and suppliers are being pressed to reduce the environmental impacts of their products and processes. As an example we have the European Union (EU) legislation on the recycling of end-of-life products, such as the directive on Waste Electrical and Electronic Equipment (WEEE) that forces the EEE producers to deal with their end-of-life products.

This evolution forced companies to design/redesign their supply chain structures in order to reduce the associated environmental impacts. Reverse flows need to be evaluated, as well as ways of recycling and/or recovering used products, whenever possible in a profitable way, with minimum environmental impacts. As a result, in most cases, new facilities will need to be incorporated into the traditional supply chain that will process end-of-life products, such as collection centres, disassembly centres and disposal facilities. The traditional supply chain is then generalized and a more complex network is obtained. To manage such network in an effective way, an optimized structure is required, where profit and environmental aspects are considered simultaneously in a balanced way.

In the last few years, some studies have been published for the design of recovery networks in a multi-objective context. Giannikos [1] developed a multi-objective model for hazardous waste transportation where the objectives were cost, total and individual perceived risks, and individual disutilities. Quariguasi et al. [2] proposed a model to evaluate the trade-offs between profitability and environmental impacts, based on sustainability requirements and Life Cycle Assessment (LCA). Ahluwalia and Nema [3] proposed a multi-objective model for the minimization of cost, perceived risk and environmental impact.

The adoption of an environmental supply chain network is recognized therefore as an important issue and some scope still exist to address systematically this problem.

In this work we propose a model that integrates design aspects of the entire closed-loop supply chain with the assessment of the associated environmental impacts. A multi-objective formulation is developed, where all relevant variables are considered in order to explore efficient and environmentally friendly logistic network configurations. The answers to questions such as: Where to place the different chain entities? Where are the higher environmental impacts? What is the best option: products disposal or product collection at customers? How can profit be improved? If environmental impacts are neglected how costs will vary? Will be evaluated through the definition of an optimal Pareto front.

A case study based on a Portuguese glass reverse supply chain is presented.

2. Model Description

As referred above, a generalized supply chain structure is designed along this work. Such structure involves a set of suppliers, producers, warehouses, costumers and sorting centres. Costumers' demands are satisfied through the forward supply chain structure and the generated end-of-life products are collected and processed in the reverse chain. These latter products may be recovered and added to the forward chain or sent to disposal, if found to be in a non-recoverable condition.

The model developed can be defined as:

Given: the supply chain super-structure; customers' demands; eco-ratios (impact result/ permitted impact); distances between entities; products' bill-of-materials; upper and lower bounds for flows; entities maximum and minimum capacities; sorting criteria to be employed at the respective centres, unit transportation costs, as well as unit storage and processing costs.

Determine: the final supply chain structure (location of installed entities); produced amounts; storage volumes; processed and disposed volumes by the recycling facilities, as well as the associated impacts or costs.

So as to minimize the global supply chain costs and/or impacts.

The resulting model is a Mixed Integer Linear Programming model (MILP) that is a generalisation of the work presented by Salema et al. [4]. An environmental impacts assessment is added and evaluated simultaneously with the costs of defining a certain supply chain structure. This assessment is made through the quantification of eco-ratios that reflect the efficiency of the impact. These are defined as the ratios between the impacts quantified and the permitted values for the same impacts. These values are calculated based on published studies and on the maximum values imposed by legislation. Five groups of related impacts were considered: water consumption, materials consumption, use of land, greenhouse and other emissions effects.

The model is characterized by five types of constraints: material balances (for each entity and product), demand satisfaction (for each customer and product), recovered flows (for each sorting centre, factory and product), impacts assessment (water, effluents,…) and maximum and minimum capacities for storage, production and transportation. In term of variables, the model involves continuous variables related to the flows amounts, impacts values and capacities designed, and binary variables that model the choice of supply chain entities.

3. Case Study

The case study that will be solved is based on the one published by Salema et al. [5]. A glass supply chain network with reverse flows is to be designed while accounting for the minimization of costs and environmental impacts. Five different entities characterize the network: suppliers, factories, warehouses, customers and sorting centres (see Figure1).

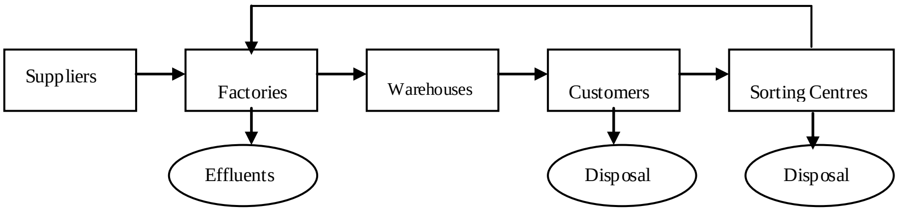

Figure 1. Schematic representation of the supply chain

Each entity, except suppliers, has an inbound and an outbound flow. Different types of materials are considered: four types of raw materials, M1 to M4 - sand, sodium, limestone and feldspar; one recovered material, C1 – used glass; three semi-final products - F1 to F3 – respectively, green, white and brown types of glass originated at the factories; and six different final products, A1 to A6 – output products of warehouses where postponement is performed based on the customers demands. After use, all the final products are considered simple glass. Factories or proper disposal are the final destination of this glass based on its physical condition. In the former case it becomes C1. Note that no distinction is made between "new" and "recycled" glass. In Fig. 2 a schematic representation of the supply chain flows is shown.

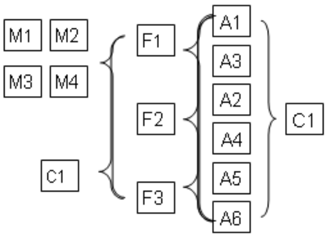

Figure 2. Supply chain flows and relationship between types of product

The Portuguese district capitals are considered as possible locations for the network entities that supply or collect products from the three customers considered, which are located at Aveiro, Lisboa and Braga. The network may have four potential suppliers (Beja, Castelo Branco, Setúbal and Viana do Castelo); two potential factories (Portalegre and Santarém); nine potential warehouses (Beja, Braga, Bragança, Castelo Branco, Coimbra, Évora, Faro, Guarda and Leiria); five potential sorting centres (Santarém, Setúbal, Viana do Castelo, Viseu and Vila Real) and nine potential disposal places (Beja, Braga, Bragança, Castelo Branco, Coimbra, Évora, Faro, Guarda and Leiria). Customers have different product needs and all demands must be satisfied. In Table 1 their demands are shown.

Table 1. Values for Demand (ton)

	A1	A2	A3	A4	A5	A6
Aveiro		6.66		1.23		
Braga		5.96	1.10		1.88	5.00
Lisboa	16.04		14.95		4.35	3.80
Total	**16.04**	**12.62**	**16.05**	**1.23**	**6.23**	**8.80**

In terms of disposal a minimum and a maximum fraction of the total supplied products, equal respectively to 0.1 and 0.6, is considered.

3.1. Results

The model was run considering two objective functions. A first one seeking the minimization of the impacts and a second one of network costs. The results in terms of network structure and flows are presented in Fig. 3, where network flows are represented, on the left for minimum impact values and on the right for minimum costs. The former involves three suppliers, one factory, one warehouse and one sorting centre, while for the latter the network is characterised by four suppliers, two factories, one warehouse and one sorting centre. For the same demand, when minimizing costs, the obtained network displays more entities than the one for the minimization of impacts. This can be explained in terms of transportation costs which tend to be reduced when costs are balanced. However if environmental impacts are the main objective, the transportation impact is not a major issue and the usage of appropriated land and of natural resources becomes dominant. As a consequence the number of entities installed is reduced.

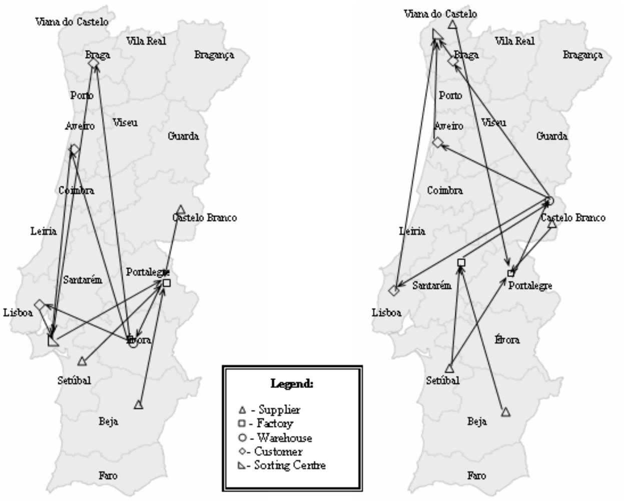

Figure 3. Network flow: minimization of impacts (left); minimization of costs (right)

As already referred, this problem deals with two objectives and therefore they should be balanced. For that a multi-objective optimization was performed leading to the Pareto front shown in Fig. 4. This provides information on alternatives that may be taken into account at the decision process. The figure shows the costs values in monetary units (m.u.) and the impact values in impact units (i.u.).

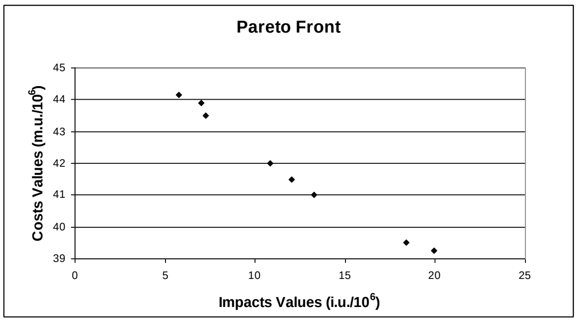

Figure 4. Pareto front obtained for the simultaneous minimization of costs and impacts

The model produces a very large amount of data. Due to lack of space, only the chains corresponding to four points at the Pareto front will be analysed: Chain 1 – Objective: to minimize environmental impacts; Chain 2 – Objective: to minimize environmental impacts with an upper limit on costs of $43.5\text{x}10^6$; Chain 3 – Objective: to minimize environmental impacts with an upper limit on costs of $41.0\ \text{x}10^6$; Chain 4 – Objective: to minimize costs.

Fig. 5 shows total environmental impacts between different cases. The transportation impact is dominant in chains 1 and 2, but exhibits very similar values in all chains. The use of water appears as the main justification for the large impact values in the other two chains, while being responsible, for all chains, for the observed differences between the total impacts values. This is a consequence of the Santarém factory displaying the highest value of water impact. Another reason is due to chains 3 and 4 having more quantity of product made in Santarém. With respect to environmental impacts due to transports, the transportation from suppliers to factories is the one that shows higher differences between chains.

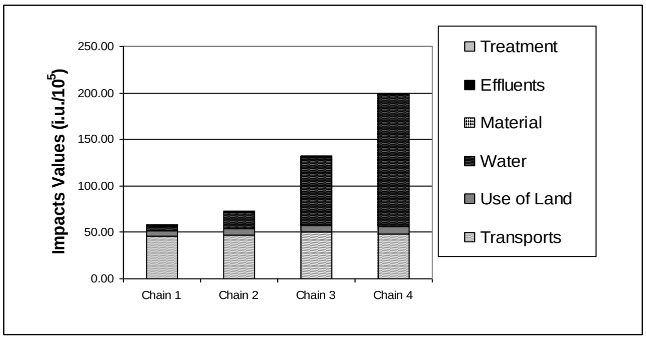

Figure 5. Total Environmental Impacts Values

When analysing costs (see Fig. 6) a significant difference is found amongst the four chains. Chain 1, where the main concern is the environment, is the more costly, while chain 4, as expected, presents the lower cost. The major cost component is transportation, which is explained by the number of entities and the specific network structure.

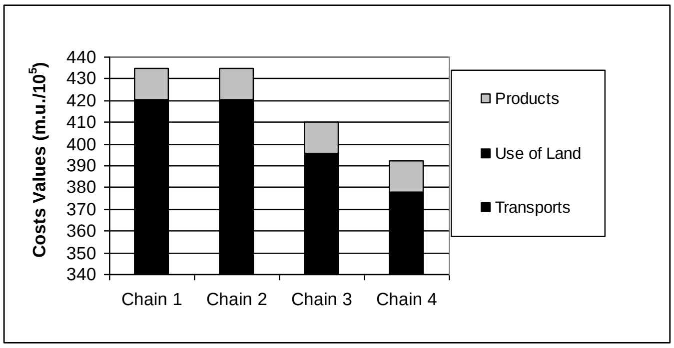

Figure 6 – Total Costs Values

All the above results where obtained running GAMS/CPLEX (built 22.2) in a Pentium 4, 3.40 GHz. The models were run on average in about 0.20 CPU secs with relative gaps smaller than 5%. In terms of statistics the model comprises 1044 variables (20 binary) and 457 to 458 constraints.

4. Conclusions

In this work, a model for the design of supply chains with reverse flows is proposed where two objectives are analysed: the minimization of cost and the minimization of the environmental impacts. Due to the presence of these two objectives a multi-objective approach was explored. A Pareto front was built which provides a large number of alternative solutions that can be used in the decision making process. Based on this the decision maker can decide on how to design the supply chain accounting for both the economical and the environmental impacts. Further work needs to be done on the model generalization, where for instance the quantification of costs associated with the impacts needs to be explored.

Acknowledgements

Funding by the FCT (contract POCTI/AMB/57566/2004) is gratefully acknowledged by the authors.

References

[1] Giannikos, I.,1998, "A multi-objective programming model for locating treatment sites and routing hazardous wastes", European Journal of Operational Research,104, 2, 333-342.
[2] Quariguasi, J., 2006, “A Methodology for Assessing Eco-efficiency in Logistics Networks”, Erasmus Research Institute of Management (ERIM). Working paper.
[3] Ahluwalia, N., 2007, “Life cycle based multi-objective optimization model for the management of computer waste”, Conservation and Recycling, Vol 51, Issue 4, 792
[4] Salema, M. I.; Póvoa, A. P.; Novais, A. Q., 2007 , “An optimization model for the design of a capacitated multi-product reverse logistics network with uncertainty”, European Journal of Operational Research,179, 1063-1077.
[5] Salema, M. I.; Póvoa, A. P.; Novais, A. Q., 2006, “Supply Chain Design and Planning with Product Return: An Optimization Approach”, in Proceedings of the POMS Conference, Boston, USA.
[6] Salema, M. I.; Póvoa, A. P.; Novais, A. Q., 2006, “A warehouse-based design model for reverse logistics”, Journal of Operations Research Society, 57, 615-629.