Design and Planning of Closed-loop Supply Chains: An Optimisation Approach

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Abstract

A general model for the design and planning of closed-loop supply chains is proposed. The model is both strategic and tactical in nature, containing two levels of decisions: the location of facilities and the planning of production, storage and distribution. Its mathematical formulation is solved using a standard Branch and Bound technique. The model applicability and accuracy are studied on a modified version of an already published case study

1 Introduction

In today's western society, environmental consciousness has aroused towards the importance of handling disposal products. The public perceived that most of such products still have some intrinsic value that must be recovered. This new rationale is leading governments to pass legislation that enforces companies to collect their used products. On the other hand, companies are discovering new opportunities of conducting business in connection with the recovery process.

This new context implies a new approach to the supply chain management where the product return must now also be accounted for. While this is so, the reverse flows are not yet fully understood and their definition not clearly established within the research community (Guide Jr. et al., 2003). Nevertheless, an increasing interest into this new concept of supply chains is clear and an increasing number of researchers have been looking into this new supply chain structure and some published models have been presented.

At a strategic level, where the main objective is the design of the supply chain, some important works have appeared. Fleischmann et al. (2001) proposed a strategic model for the design of the global chain, where forward and reverse flows are integrated for a single product, but where no limiting capacities are considered. Jayaraman et al. (2003) looked into the reverse distribution problem and developed a model where the forward flow is not considered. Fandel and Stammen (2004) presented a general MILP model for extended strategic supply chain management, based on a two-step time structure, but no testing of model adequacy was explored. In all previous models, the focus is placed on network design of forward and reverse flows for products with a lasting identity. Finally, Salema et al. (2004) developed a capacitated multi-product design network model where forward and reverse flows were considered. The flows differed not only in terms of structure but also in the number of products involved.

At the tactical or production/distribution level, few works have addressed important aspects of supply chain management such as: How to incorporate return products into production? Should used products be separated from new products? Where and how return products are to be disassembled? Some MILP models have been proposed for the production/distribution problem but most of them relate only to new products. When the reverse flows are added to the supply chain, this problem has to be reconfigured so as to integrate used products into the production planning. Arntzen et al. (1995)

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reported the study of the restructuring of a supply chain developed for Digital Equipment Corporation. The proposed model accounted for the products' bill of materials, multistage manufacturing and inventory planning in a multinational environment. Although an interesting work, it only models the forward supply chain.

From the above description, it can be concluded that the simultaneous design and planning of forward and reverse networks is a working field not yet fully explored (Goetschalckx et al., 2002). Thus, in the present paper, a model for the design of a supply chain network with reverse flows is proposed. Both strategic and tactical aspects are integrated within one model. Besides the design feature, the planning of production, storage and distribution is also accounted for. This is achieved through the use of two interconnected time scales: a "macro" time, where strategic decisions are accounted for and a "micro" time where the planning is performed.

The paper is structured as follows. The problem is first defined and the model is briefly presented. Then an example, based on a previously published case-study, is applied. Finally, some final remarks are drawn.

2 Problem description

In the studied network (Figure 1), four different agents interact: factories, warehouses, customers and disassembly centres. Customers have a demand that needs to be satisfied. Once used some of the supplied products will be returned for remanufacturing. Thus, the forward flow links factories to customers through warehouses, while the reverse flow links customers to factories through disassembly centres. No direct link is allowed between customers and factories.

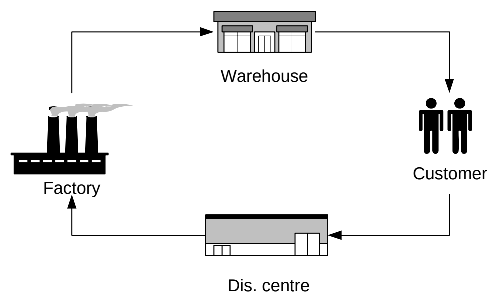


Figure 1: Closed-loop supply chain.

Traditionally, production planning is mostly concerned with the transformation of raw materials into final products with a view to meet customers' demand. However, in a close loop context, products once used are collected, disassembled and sent back to factories. The disassembly is performed in disassembly centres, where sub-assemblies are assessed and sent to factories and/or disposal. Thus three different groups of products actually flow in the network: forward products from factories to customers through warehouses, reverse products from customers to disassembly centres and sub-assemblies from disassembly centres to factories. Inventories are allowed in all facilities and are limited to their maximum levels. Maximum and minimum limits are also imposed on production levels and distribution flows.

Within this framework, three levels of decisions are taken within two interconnected time scales: a "micro" time scale, where production, storage and distribution is planned, a "macro" time scale where customers' demand and return is satisfied, and the time horizon, where the sites where to locate facilities are chosen. These time scales can be years/months, years/trimester, month/days or whichever combination suits the problem.

Travel times are modelled between network levels. They are defined as the number of "micro" time units needed for a product to flow from its origin to its destination. If travel times are set to zero then a multi-period location/allocation network model is obtained.

Lastly, a cost function is minimized. Costs include investment and operational costs and production, storage, distribution, disposal and penalty costs (for non-satisfied demand or return).

In short, the proposed model can be stated as follows.

Given:

- the investment costs,
- products' bill of materials,
- the relation between forward and reverse products,

- travel time between each pair of interacting network agents,
- the minimum disposal fraction,
- forward product return fractions,

for each macro period and product:

- customer's demand volume,
- the unit penalty costs for non satisfied demand and return,

and in addition, for each micro period and product:

- the unit transportation cost between each pair of interacting network agents,
- the maximum and minimum flow capacities,
- the factory production unit costs,
- each facility unit storage cost,
- the unit disposal cost,
- the maximum and minimum production capacities,
- the maximum storage capacities and
- the initial stock levels.

Determine the network structure, the production levels and storage levels, the flow amounts and the non-satisfied demand and return volumes.
So as to minimize the global supply chain cost.

The resulting model is a Mixed Integer Linear Program (MILP) which involves 14 types of variables and 24 types of constraints. This formulation considers the following types of variables: one production variable, four flow variables, four stock variables and two for the non-satisfied demand and return, all as continuous variables, and three binary variables related with the location of the three different kinds of facilities.

In terms of constraints, the model comprehends four material balance equations, one constraint that assures demand satisfaction, one that assures return satisfaction, one that allows the disposal option, three for maximum storage, one for minimum and another one for maximum production limits and, finally, twelve groups of constraints to assure minimum and maximum flow capacities.

3 European Case

3.1 Case description

This case was created based on a company that operates in Europe (adapted form a previous published case, Salema et al., 2005). This company needs to determine the network design for a supply chain that will involve three forward products (F_1, F_2 and F_3), two return products (R_1 and R_2) and four sub-assembly components (C_1, C_2, C_3 and C_4).

At the strategic level customers are grouped into 28 clusters, where each cluster is named after the city it represents. Customers' clusters, from now on designated simply as customers, are respectively located in Amsterdam, Barcelona, Berlin, Brussels, Copenhagen, Dublin, Düsseldorf, Essen, Frankfurt, Glasgow, Hamburg, Helsinki, Lille, Lisbon, Liverpool, London, Lyon, Madrid, Nuremberg, Oslo, Palermo, Paris, Rome, Rotterdam, Stockholm, Turin, Valencia and Vienna.

Five of these cities are possible sites where to locate warehouses and/or disassembly centres (Amsterdam, Brussels, Paris, Turin and Vienna). For factories there are only three possible locations: Amsterdam, Brussels and Vienna.

In terms of time, a macro period is defined over five years and a micro period over four trimesters per year: macro period = "year" and micro period = "trimester". Since the model considers a horizon of five years, some data has to be estimated. These include the demand volumes as well as variations in costs over the years. These estimates were based on some assumptions: 1) transportations costs are proportional to the distance between each city; 2) after the first year an actualization rate of 3% (or some other convenient value) is applied to all costs; 3) in the first year, customers' demand is made equal to a fraction of the city inhabitants (a value between 0.04 and 0.055) while for the remaining years, this value is modified by a variation factor (ranging from 0.98 to 1.05), allowing for an increase or decrease in the demand volumes.

After use, products F_1 and F_2 are returned as R_1 and product F_3 as R_2. In terms of return fractions, only 60% of F_1 is collected while F_2 and F_3 have a return fraction of 80%; the problem also assumes zero initial stock levels and the disposal fraction is set to 0.1, which means that al least 10% of returns have to undergo disposal. Minimum and maximum capacities are defined for production ($1*10^6$ and $3*10^6$, respectively); maximum, but no minimum, limits are imposed on flows between factories/warehouses and disassembly centres/factories; all flows from and to customers have maximum and minimum limits; travel time is set to nil, which seems a reasonable assumption given the chosen time scale (years/trimester) and the particular geographical area under study.

3.2 Results

The resulting MILP model was solved by GAMS/CPLEX (built 21.1), in a Pentium 4, 3.40 GHz. The model is characterised by 25 822 variables (6313 binary) and 22 049 constraints, and took about 3580 CPU seconds to solve (0.01% optimality gap). The optimal value found is $3.8x10^9$ currency units.

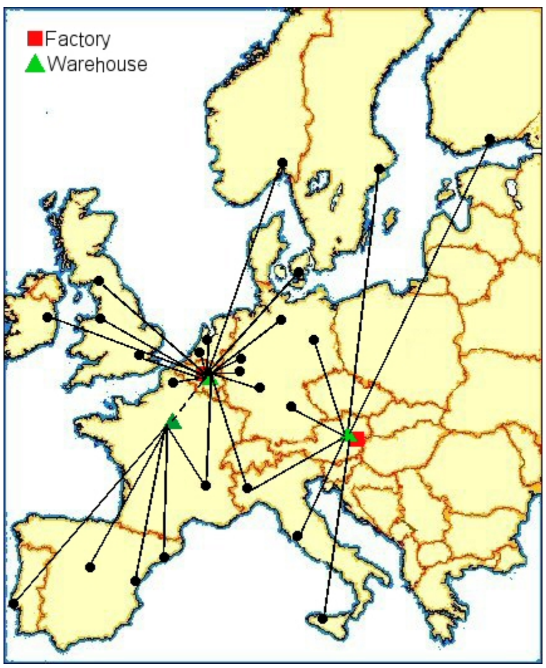
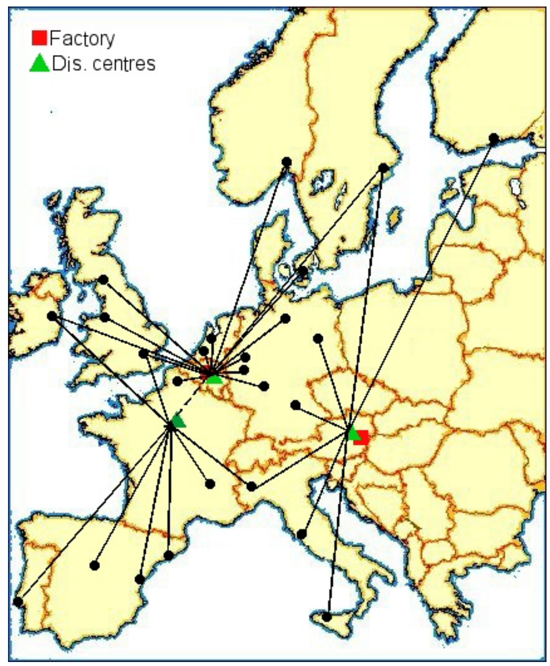


Figure 2a: Forward network.



2b: Reverse network.

The optimal network (Figure 2) is characterized by two factories located in Brussels and Vienna. These two cities were also chosen to locate warehouses and disassembly centres. A third warehouse and a third disassembly centre are located in Paris; both these facilities are connected with Brussels factory. In Figure 2a and 2b, respectively, the optimal forward and reverse networks are presented. One can observe that they have a very similar structure. Due to the way transportation costs were estimated, those three sites act as geographical centres.

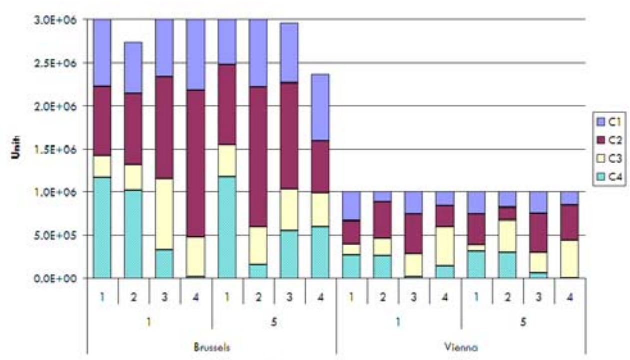


Figure 3: Some production plan examples.

Both networks assure that all twenty eight customers have their demand and return satisfied.

Concerning the tactical level of decision three different analyses can be made, respectively, for production, storage and distribution. As the model produces a large wealth of information, only some examples will be presented.

In terms of production, all four new sub-assemblies are produced in both factories. In Figure 3, we see an example of the production plan for all four trimesters of the first and fifth year. It should be noted that Brussels factory produces almost always at the maximum established limit, while Vienna factory has its production levelled to the minimum capacity.

Regarding inventories, a zero stock policy is foreseen.

An example of the distribution plan between factories and warehouses is shown in Figure 4 for the first and fifth year. The highest values are found for the flows between facilities located in Brussels. Among the existing warehouses, Brussels warehouse is the one with the higher volume of activity. In Figure 5 one can see the flows to Turin's customer. This is one of the few customers that are supplied by more than one warehouse. It is interesting to note that product F_1 is only supplied by Vienna warehouse; this same warehouse supplies only a fraction of the demand for product F2; all the remaining demand is satisfied by Brussels warehouse.

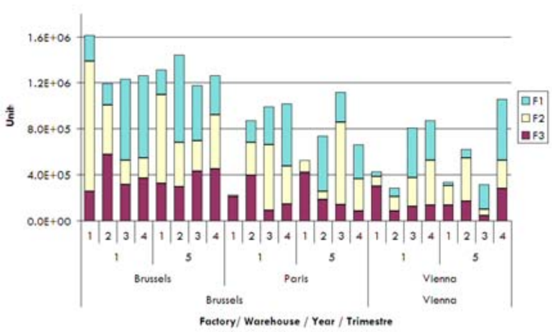


Figure 4: Flow between factories and warehouses.

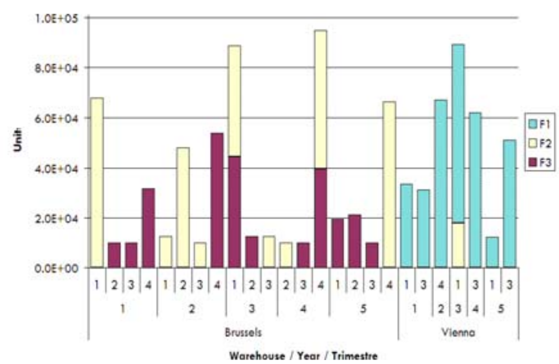


Figure 5: Flows to Turin customer.

In Figure 6 are shown the flows of two customers (Barcelona and Lisbon) that have their returns collected by Paris disassembly centre. Note that, when these flows occur, they have to meet minimum levels, which explains why all represented flows are of, at least, 10000 units. The difference between the return volumes of these two customers are related with their demand volumes. Finally, the flows leaving Brussels and Paris warehouses, for the first and fifth year, are shown in Figure 7. These flows go either to Brussels factory or to "f0", the latter representing the disposal option. Note that Brussels flows are limited by the maximum capacity allowed.

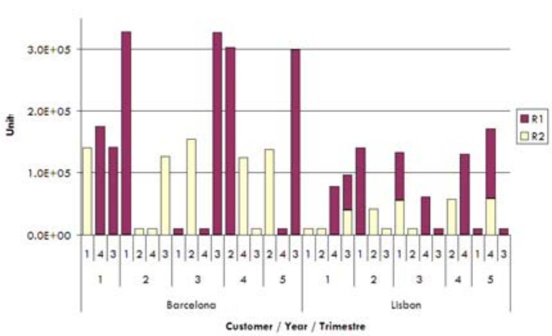


Figure 6: Some inbound flows to Paris dis. centre.

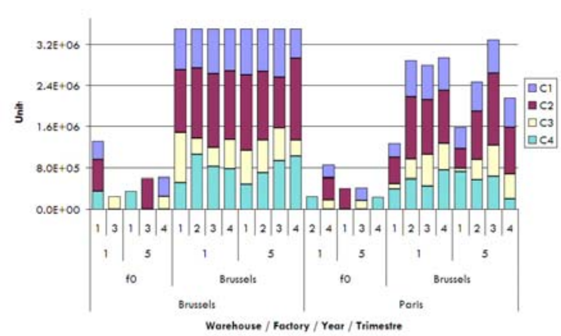


Figure 7: Some dis. centre outbound flows.

4 Conclusions

In this work, a model for the design and planning of closed-loop supply chains is proposed. By incorporating a strategic and a tactical decision levels, we are not only able to find the best locations to install a set of facilities, but also to estimate the associated optimal production, storage and distribution plans.

A European case, previously published, is modified in order to test the model applicability and adequacy. The results obtained show that the proposed model deals satisfactorily with problems with a considerable degree of detail and complexity. Thus, the proposed model appears as a promising decision support tool to help the decision-making process in the strategic and tactical planning of multi-product capacitated closed loop supply chains.

As future work and in order to speed up the solving process, we intend to investigate the application of decomposition methods, either generic (ex. Benders Decomposition) or specially developed for this model. With the same aim, some tailored cuts are being considered.

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