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Design and Planning of Supply Chains with Reverse Flows

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Abstract
A multi-product model for the design of global supply chains with reverse flows is proposed. Two levels of decisions are considered, one strategic and one tactical. The first is modelled through a macro perspective of time where the determination of the network structure and flows is accomplished. At tactical level, a micro perspective of time is considered, where production planning and inventory management are addressed in detail. A mixed integer linear programming formulation is developed which is solved with standard Branch and Bound techniques. The model accuracy and suitability are studied using a case study.

Keywords: Supply Chain design, Optimization, Reverse Logistics, Planning.

1. Introduction

In modern society, used products constitute a major challenge. Governments are facing overflowed landfills, while creating legislation to shift product management responsibility towards the producers. Used/disposed products are now placed in a different perspective, as company managers perceive new business opportunities whereby these products should be returned to factories for remanufacturing /recycling. Consequently, the supply chain must be extended and no longer terminate at the end customers, but account also for the products return.

Only recently the scientific community started looking into this problem. Thus the reverse logistics problem appears as an emerging field where only a limited number of models have been, so far, presented in the literature. These are essentially case study dependent and mostly consider the reverse flow on its own and not as an integral part of the supply chain. As the most generalized published models, one should refer to: Fleischmann et al. (2001), where forward and reverse flows of a given product are integrated, with no limiting capacities in the involved facilities and flows; Jayaraman et al. (2003), who proposed a MILP model for the reverse distribution problem, without taking into account the forward flow; Fandel and Stammen (2004), that proposed a MILP general model for extended strategic supply chain management, based on a two-step time structure, but where no testing of adequacy to any example/case was explored; and finally Salema et al. (2004) who developed a capacitated multi-product design

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network model where forward and reverse flows were considered, the flows differ not only in terms of structure but also in the number of products involved. Within these few works, one important area of research not yet explored, is the simultaneous design and planning of such structures (Goetschalckx et al., 2002). In the present paper, we look into this issue and propose an optimal multi-product supply chain design model where both forward and return flows are integrated considering simultaneously the design and planning of such structures. A Mixed Integer Linear Programming formulation is developed where two different perspectives are employed for the treatment of time: a macro perspective (strategic), for the determination of the network structure and flows, and a micro, more detailed perspective (tactical), for the production planning and inventory management. An illustrative case-study is solved showing the model applicability.

2. Problem Definition

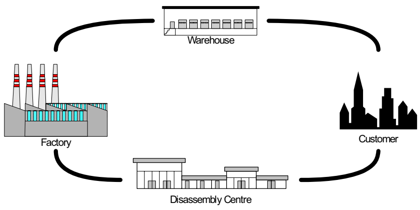

Figure 1: Distribution network with reverse flows.

Figure 1 shows a schematic representation of a supply chain network with reverse flows. A two echelons forward distribution network is considered where factories are linked to customers through warehouses. No direct connection, factory-costumer, is allowed. The same applies for the reverse flow where a two echelons structure is also present, customers being linked to factories through disassembly centres. Again, customers cannot send their products directly to factories, since products must pass through disassembly centres. Forward and returned products might be treated as independent since we consider that original products may loose their identity after use (e.g. paper recycling - paper products after use are simply classified as paper). However, if required, it is also possible to track the same product in both flows. Furthermore, a disposal option is considered within the structure in study. At the disassembly centres if collected products are found to be unsuitable for remanufacturing, a disposal option is made available.

Using these structural options the model considers two levels of decisions at different time scales. A "macro time" scale, where the supply network is designed, and a "micro time" scale, where planning activities are set (e.g. macro production and/or storage planning). These time scales can be years/months, years/trimester, month/days or whichever combination suits the problem. The chosen facilities will remain unchanged throughout the time horizon while the throughput will undergo changes.

Flows are not necessarily instantaneous (customers will not have their demand satisfied in the same time period when products are manufactured) and thus travelling times might be considered. A travelling time is modelled as the number of micro time periods that a product takes to flow from its origin to its destination. If all travelling times were to be set to zero, a multi-period location/allocation model would be obtained.

Finally, a profit function is assumed for the objective function where revenues and transfer plus selling prices are considered. The former are defined whenever there are products flowing between facilities (from factories to warehouses or from disassembly

centres to factories) and the latter whenever products are sent to customers by warehouses or collected by disassembly centres. In terms of costs different terms are identified: investment costs (whenever a facility is chosen), transportation costs, production costs, storage costs and penalty costs (for non-satisfied demand or return).
In short, the proposed model can be stated as follows.

Given:

- the investment costs
- the amount of returned product that will be added to the new products
- travelling time between each pair of network agents
- the minimum disposal fraction

and for each macro period and product:

- customers' demand and return values,
- the unit penalty costs for non satisfied demand and return,

and in addition, for each micro period:

- the unit transportation cost between each pair of network agents,
- the maximum and minimum flow capacities,
- the factory production unit costs,
- the facilities unit storage costs,
- the maximum and minimum production capacities,
- the maximum storage capacities,
- the initial stock levels,
- the transfer prices between facilities,
- customers' purchase and selling prices.

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

3. Iberian Case

3.1 Case description

This example was created based on a company that operates in the Iberian Peninsula. This company needs to determine the network design for a supply chain that will involve two forward products (F1 and F2) and one single returned product (R1).
At the strategic level customers are grouped into 16 clusters, where each cluster is named after the city it represents. Customers' clusters, from now on designated simply as customers, are respectively located in Barcelona, Bilbao, Braga, Coimbra, la Coruña, Granada, Lisbon, Madrid, Malaga, Oviedo, Porto, Santander, Saragossa, Seville, Valencia and Valladolid.
Six of these cities are possible sites to locate warehouses and/or disassembly centres (Barcelona, Bilbao, Lisboa, Madrid, Porto and Sevilla). For the factories there are only two possible locations: Lisbon and Madrid.
In terms of time, a macro period is defined over ten years and a micro period over twelve months per year: macro period = "year" and micro period = "month". Since the model considers a horizon of ten years, some data have to be estimated. These include the demand and return volumes as well as variations in costs over the years. These

estimates were based on some assumptions: transportations costs are proportional to the distance between each city and after the first year an inflation rate of 3% (or some other convenient value) is applied to these and all other costs; if flows link cities in different countries, a tax is applied to the corresponding transportation cost namely, 6% from Portugal to Spain and 3% from Spain to Portugal; in the first year, customers' demand is made equal to a fraction of the city inhabitants (a value between 0.8 and 0.9) while in the remaining years a variation factor (ranging from 0.98 to 1.08) is considered, allowing for an increase or decrease in the demand value; in each year, customers' returns is set as a 0.8 fraction of the corresponding demand.

The problem also assumes zero initial stock levels; for product recycling F1 incorporates 0.6 of product R1 and product F2 incorporates the remaining 0.4 of product R1; the disposal fraction is set to zero; minimum and maximum capacities are defined for production ($0.8*10^6$ and $1.0*10^6$, respectively); no limit is imposed on flows; travelling time is set to nil, which seems a reasonable assumption given the chosen time scale (years/month) and the particular geographical area under study.

3.2 Results

The resulting MILP model was solved by GMAS/CPLEX (built 21.1), in a Pentium 4, 3,40 GHz. The model is characterised by 46 337 variables (14 binary) and 5 703 constraints and took about 392 CPU seconds to solve (0% optimality gap). The optimal value found for the objective function is $96x10^9$ currency units and the optimal network is characterised by a single factory location (Madrid).

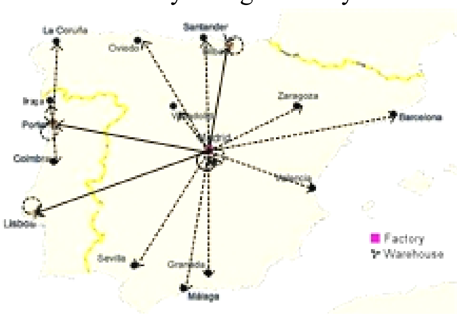

Figure 2a: Forward networks

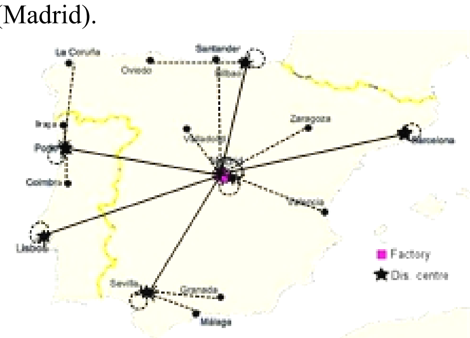

Figure 2b: Reverse networks

In the forward flow, the Madrid factory serves four warehouses (Bilbao, Lisboa, Madrid and Porto). The associated connections are depicted in Figure 2a: solid lines link the factory to warehouses and dotted lines connect warehouses to customers. One can see that Lisboa and Bilbao have just one customer and that Madrid acts has a geographical centre.

Every warehouse supplies the customer located in the same city, while there is one single customer which is served by a warehouse outside the country (Coruna is served by Porto). The number of connections between the two countries is therefore small, which is a result of the taxation imposed for flows between countries. Finally, all customers had their demand fully supplied.

In terms of the reverse network (Figure 2b), all six different locations were chosen for the disassembly centres (Barcelona, Bilbao, Lisboa, Madrid, Porto and Seville). As in

the forward network, every disassembly centre serves the customer located in the same city.
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.

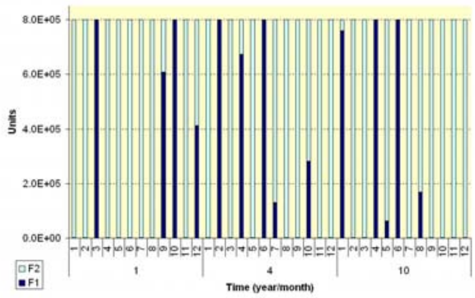

Figure 3: Factory production plan.

In terms of production, Madrid factory operates continually at the minimum level. To meet demand fluctuations, this factory has the products returned by the disassembly centres. To illustrate the optimal production plan, the first, fourth and tenth years are depicted in Figure 3.
In terms of storage, the optimal solution leads to a zero stock policy. This is a result of the negative impact that storage has on the objective function (i.e. inventory is costly).
Finally in terms of distribution, four examples are given. Each one refers to a different network level.

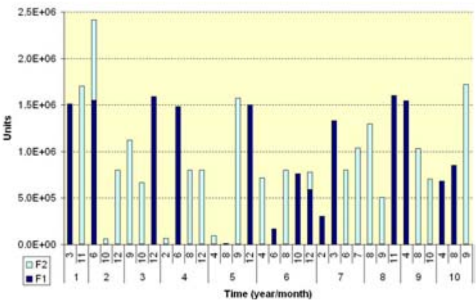

Figure 4: Distribution flows between Madrid and Lisboa.

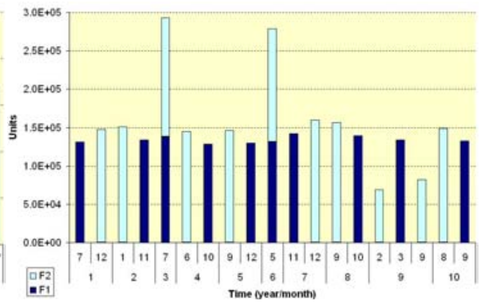

Figure 5: Demand served to Braga's customer.

Figure 4 shows in detail the flows between the factory and the warehouse located in Lisboa. The relaxation of the capacity constraints resulted in very dissimilar flow patterns. In Figure 5, Braga's customer supplying plan is depicted. The difference between amounts supplied has to do with the simultaneity of supplies received by this customer, as noted in the third and sixth years. On the contrary, in the ninth year there are three separate visits. In the remaining years, every product is supplied in one single separate delivery.
With regard to return volumes, Figure 6 shows the total return of product R1 between customers and disassembly centres. The dissimilarity among values is a consequence of

the customers return volumes. Lastly, the return of Lisboa disassembly centre is depicted in figure 7. One can see that each year returns are sent to remanufacture (Madrid factory, labelled Mad) as well as to the disposal option (f0). However, the number of times these activities are performed, varies between once and twice a year.

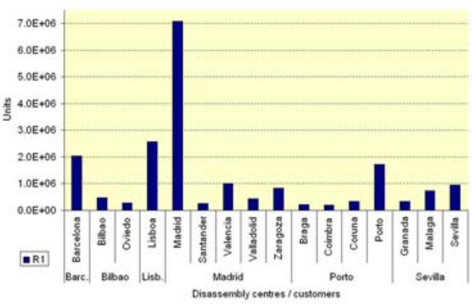

Figure 6: Total return for the first year.

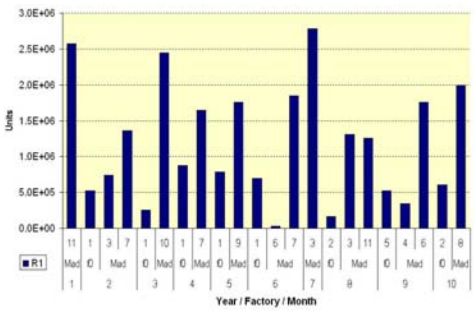

Figure 7: Lisboa disassembly centre return flows.

4. Conclusions

In this paper, a multi-period, multi-product design model for a supply chain network with reverse flows is proposed. Two time levels are modelled allowing the establishment of two different levels of decisions: a strategic level defining the network design of the supply chain and a tactical level defining the production, storage, distribution and returning planning. The obtained MILP formulation is fairly flexible since several products can be considered in both networks; different time units can be correlated (years/semesters, years/months, months/days…); limits can be imposed on flows, production and storage capacities; and different travelling times are allowed.

The mathematical formulation which supports this model, while it is likely to increase significantly in complexity with the problem dimension, still appears as an important tool to help the decision making process at the strategic and tactical levels of the supply chain management decisions. In order to overcome the computational burden of such a formulation, different solution techniques are now being explored to speed up resolution. Further research is also being undertaken with a view to both strengthen the model formulation and to treat production planning with greater detail, with the introduction of bills of materials.

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