Dynamic network design model with reverse flows

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Abstract

Much attention is currently given to the study of supply chains. Most studies are, however, only concerned with forward chains, rendering reverse chains a field insufficiently covered. Few optimization models addressing either the design of reverse networks or the simultaneous design of forward and reverse networks have been presented.

We propose a MILP model for the design and planning of an integrated forward and reverse chain. While minimizing cost, the network structure is defined simultaneously with production and storage planning. Dynamic aspects are accounted for using a two-time scale, fully interconnected structure, where at a macro time the network design is performed and at a micro time the planning is optimised.

The deterministic model is extended and a scenario approach is applied to account for uncertainties in demand and return of products.

A case study is solved and a common structure to all scenarios is obtained, while scenario dependent policies are defined for distribution, production and storage. The model generality is corroborated with good performance results.

1 Introduction

In the last decades, end-of-life products have been looked upon by society, in general, and researchers in particular as being a challenging problem. The supply chain no longer finishes when product reaches the final customer, but it has now to account for their return, back to processing facilities. Although relevant, the reverse flow has yet to be considered as a strategic matter (Guide Jr et al., 2003).

The optimal design of global supply chains has been a taxing problem, mostly when uncertainties have to be accounted for. There are several sources of uncertainty in global supply chains, in particular when considering large supply chains, with an international dimension. Some of these sources derive from variable transportation times, non-deterministic demand, variability of market prices, exchange rate fluctuations and political instability (Vidal and Goetschalckx, 2000). Moreover, when considering reverse flows, some major sources of uncertainty appear associated with the volume and quality of returned products, the origin of returned products and the demand for recovered products.

To the authors best knowledge, very few optimization models for the design of supply chains with reverse flows have been proposed where uncertainties are modelled by the use of scenarios. One of the major facts is that the consideration of uncertainties makes MILP models very hard to solve. However, an optimal or a near-optimal solution of these models gives managers useful information when they face complex decisions on how to configure supply chains in a dynamic environment.

Realff et al. (2000) propose a mixed integer formulation for the strategic design of reverse production systems (RPS). A robust optimization framework is used where the objective is, as described by the authors, "the minimization of the maximum deviation of the performance of the network from the optimal performance under a number of different scenarios". In order to demonstrate the approach, a case study of carpet recycling is studied and a model is developed, which enables the decision maker to develop insights on the reverse production system performance under a number of alternatives. This is especially important when considering RPS infrastructure expansion over a planning horizon.

Salema et al. (2003) study the problem of designing simultaneously the forward and reverse networks. The proposed model is fairly general as it incorporates facility capacity limits, multi-product and uncertainty. In it, a scenario approach is used to model uncertainty. An illustrative case is presented, which allowed the model generality to be corroborated within very satisfactory computational times.

Listes and Dekker (2005), propose a stochastic approach to the case study of recycling sand from demolition waste, in The Netherlands. In it, the uncertainty is related to the demand sources and quality, i.e. from which locations the sand to be recycled is originated and its characteristics. The scenario approach was used to extend a previous published work. The authors concluded that “given the existing computational power and using an adequate modelling it is nowadays possible to apply stochastic programming techniques to practical situations of logistic networks design”.

Later on, with the purpose of setting up a generic stochastic approach for the design of networks, where return channels were considered, Listes (2002) tested a published methodology on several instances of a model he proposed. This model considers a one-echelon forward network combined with a two-echelon reverse network. The uncertainty is handled in a stochastic formulation by means of discrete alternative scenarios. The author concluded that computational results showed a consistent performance efficiency of the method, when applied to the location model in question.

Also recently, Salema et al. (2004) propose a strategic and tactical model for the design and planning of supply chains with reverse flows. The authors considered the network design as a strategic decision, while tactical decisions are associated to production, storage and distribution planning. The integration of these two kinds of decisions is achieved by considering two interconnected time scales: a macro and a micro time. The model was applied to an already published case study, using standard Branch and Bound techniques. The obtained results corroborate the model adequacy to real problems.

As mentioned above, the uncertainty is a key factor when simultaneously designing forward and reverse networks. In this paper and based on the model of Salema et al. (2004), a scenario approach is used to account for the uncertainties on demand and return volumes, as well as on the inflation rate used to update all costs involved in the model.

In section 2, the scenario approach is established. Next, the problem is defined and the impact of the proposed approach on the model formulation is analysed. A case study is then presented to illustrate the applicability of the model. Finally some conclusions are drawn and some future work is proposed.

2 Modelling uncertainty

In this work, uncertainty is modelled through the establishment of a small number of discrete scenarios. For each scenario, the random variable assumes deterministic values. The objective is to find the solution that will perform better under all scenarios. The scenario approach that will be described follows the work of Birge and Louveaux (1997), where a two-stage stochastic programming is defined.

For this two-stage stochastic model, these authors split the decision variables in two major groups: first-stage and second-stage. The ones 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. Within our model, these variables are the location variables, i.e. they are the binary variables defined for the choice of each type of facility, which represent the strategic decisions. The second-stage variables are related with the decisions that can be reviewed after the scenario occurrence. In our model, these are the tactical decision variables and it implies that production, storage and distribution planning decisions can be made after demand is known.

So, consider S as the set of all possible scenarios and $s \in S$ 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 costs related to the opening of the facilities and c the vector containing the remaining coefficients in the objective function. The deterministic model for a particular scenario s, is defined as:

$$\begin{aligned} \min \quad & c_s x + fy \\ s.t. \quad & A_s x \leq a_s \\ & B_s x \leq Cy \\ & y \in \{0,1\}, x \geq 0, x \in \mathbb{R} \end{aligned}$$

where A_s, B_s and C are matrixes and a_s is a vector.

The solution of this model gives the best network design and global planning for any individual scenario. Based on this, the two-stage stochastic model is composed of two models, as follows:

$$\begin{aligned} \min \quad & E\left[\Theta(x,s)\right] + fy \\ s.t. \quad & y \in \{0,1\} \end{aligned} \quad \text{with} \quad \begin{aligned} \min \quad & \Theta(x,s) = c_s x_s \\ s.t. \quad & A_s x_s \leq a_s \\ & B_s x_s \leq Cy \\ & x_s \geq 0, x_s \in \mathbb{R} \end{aligned}$$

where $E\left[\Theta(x,s)\right]$ is the expected value of $\Theta(x,s)$.

As one wants to model a finite number of discrete scenarios, the expected value function becomes an ordinary sum. Thus, explicitly introducing in the first stage model the second stage variables, the following mixed integer linear model is obtained.

$$\begin{aligned} \min \quad & z = \sum_{s \in S} \pi_s c_s x_s + fy \\ s.t. \quad & A_s x_s \leq a_s \\ & B_s x_s \leq Cy \\ & y \in \{0,1\}, x_s \geq 0, x_s \in \mathbb{R} \end{aligned}$$

where π_s is the probability of scenario s.

For further details, please refer to the work of Birge and Louveaux (1997).

3 Problem definition

The deterministic model for this work considers a two-echelon forward network, where factories are connected to customers through warehouses, together with a two-echelon reverse network were customers are now connected to factories through disassembly centres. No direct link between customers and factories is allowed.

Both networks are multi-product. After use, products may loose their identity (e.g. paper recycling - after use the paper products are simply classified as paper), thus they are treated as independent products. However, if necessary the same product can be tracked down in both networks.

Although disassembly centres are often viewed as warehouses of the reverse flow, in fact they assume a different role. When products are collected from customers, their quality is usually unknown. In these centres, returned products go through an inspection phase where they are sorted according to their condition. As some of the products may be in too bad a condition to be remanufactured, they are sent to proper disposal. In order to allow for this special task, a disposal option was modelled in the disassembly centres.

As mentioned above, the proposed model allows for two different types of decisions: strategic and tactical. This feature is made possible through the use of two interconnected time scales. A “macro time” scale where the design of the network is defined and a “micro time” where production, storage and distribution are planned. These time scales can be years/months, years/trimesters, month/days or whichever association suits the problem. One should note that the chosen facilities will remain unchanged throughout the time horizon while the throughput may undergo changes.

Traditionally, multi-period location/allocation models consider that flows between the existing entities are instantaneous. However, due to the two-time scale, some cases may occur where the micro time and the travel time between two sites are of the same scale. So, the travel time is modelled as the number of micro time periods that a product takes to go from its origin to its destination (Salema et al., 2004). If all travel times were to be set to zero, a multi-period location/allocation model would be obtained.

Finally, a cost objective function is considered. The different cost terms added are: investment costs (whenever a facility is chosen), transportation costs, production costs, storage costs and penalty costs (for non-satisfied demand or return).

A schematic description of the model adapted from Salema et al. (2004) can be stated as:

Minimize Global supply chain cost
subject to Macro time constraints
Demand
Return
Disposal
Micro time constraints
Production: material balance and capacities
Warehouse storage
Disassembly centre storage
Network balance
Transportation flows

In the case study that follows, this model was modified to allow for the simultaneous design and planning over the established scenarios. Using the first and second stages model approach, defined in the previous section, we considered all constraints as part of the second stage model; structural decisions are assumed in the first stage, while operational variables are used in the second stage. In terms of objective functions, the cost terms related with investment were assigned to the first-stage, while all other terms were allocated to the second-stage.

4 Case study

To illustrate the accuracy and applicability of the model, an already published case study is used (Salema et al., 2004). In here, a company settled in the Iberian Peninsula wants to study a network with a forward flow of two families of products (P_1 and P_2) and a reverse flow with a single product family (R_1). Two locations were considered to establish the factories: Madrid and Lisboa. For warehouses and disassembly centres, five locations were proposed: Barcelona, Madrid and Malaga, in Spain, and Lisboa and Porto, in Portugal. From now on product families are referred simply as products.

Regarding time, the macro time was defined over ten years while the micro time involves twelve months each year. All travel times were set as zero, since the allocated times fall below the micro time unit (one month).

4.1 Case data

Product demand and return were divided into customers' clusters, located in ten different cities: Barcelona, Bilbao, Madrid, Malaga, Oviedo, Sevilla and Valencia (in Spain) and Braga, Lisboa and Porto (in Portugal). Demand and return parameters were set in the macro time unit.

As aforementioned, demand and return are scenario dependent. It was assumed that, in all scenarios and for the first year (T_1), the demand value is proportional to each city population. In terms of return values, they are a fraction of each customer total demand. All fractions are given in Table 1.

Table 1: Demand and return fractions for each scenario.

		Scenario 1	Scenario 2	Scenario 3
Demand	P_1	0.8	0.6	0.9
	P_2	0.9	0.65	0.92
Return	R_1	0.8	0.95	0.6

To reflect demand changes, throughout the remaining nine years (T_2 to T_{10}), a factor was applied over the number of inhabitants. This factor changes on a yearly basis and, in each scenario, it follows a different pattern. In Table 2, the different values used in the established scenarios are shown.

Table 2: Demand variation factor.

Scenario\Years	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}
S_1	1	1.02	1.05	0.98	0.99	1	1.08	1.06	1.02	1.01
S_2	0.815	0.79	0.804	0.815	0.802	0.806	0.797	0.775	0.805	0.787
S_3	1.5	1.44	1.55	1.39	1.48	1.49	1.56	1.37	1.56	1.45

In order to have a better view on how this factor affects the demand volume, Figure Figure 1 shows the demand values of product P_1 for the customer located in Braga, where each series belongs to a different scenario (z-axis). From this figure, it is clear the effect of the different demand variation factors. The scenario with the lowest demand volume is scenario 2, while scenario 3 is the one with the highest volume. For all other customers, the demand pattern is similar (not shown).

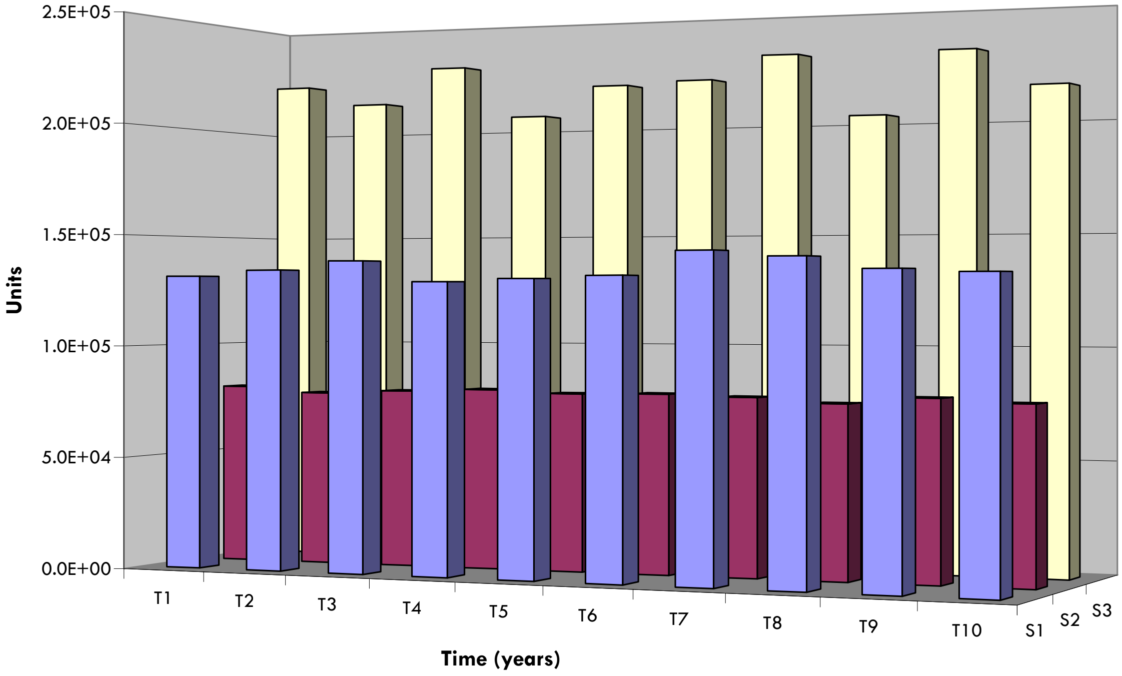

Figure 1: Braga' demand patterns for product P_1 and three scenarios, over the planning horizon.

Note that population does not change so much during a so short period of time. However, this was an efficient way to reflect demand and return changes over time.

Lower and upper bounds were set for production. These limits assure that production will not change radically during the time horizon, which is a common constraint in real world cases. Maximum storage capacities were also imposed on factories, warehouses and disassembly centres. Concerning flows, a maximum limit was imposed over the time horizon. A minimum flow limit was set whenever the flow occurs, i.e., any flow is either zero or greater or equal to a pre-established lower bound. All mentioned bounds remain unchanged over the time horizon and are not scenario dependent.

The initial stock level, as well as the disposal fraction γ, were set to zero. This last condition implies that the model can decide that factories receive all products collected by the disassembly centres.

In terms of costs, they can be divided into three groups: investment, production plus storage and distribution. Investment costs occur whenever a facility is chosen to be opened and only once. Production and storage costs are unit costs that are updated on a yearly basis according to an inflation rate. This inflation rate is different for each scenario. The values applied are given in Table 3.

Table 3: Inflation rate and ocurrence probability.

	Scenario 1	Scenario 2	Scenario 3
Inflation rate	0.03	0.06	0.015
Probability	0.5	0.15	0.35

Distribution costs are unit costs that are distance dependent. As the previous costs, these are updated with the inflation rate. One other feature of these costs is that a tax is imposed when the flows cross borders.

Penalization costs were assumed equal for all products and customers. Again the previous methodology was used; they are updated with an inflation rate.

Finally, a discrete probability function was assumed and is presented in Table 3.

For further detail on the data, please refer to Salema et al. (2004). In it, a complete description of all the data is given.

4.2 Results

The case was run in a Pentium IV, 3.40 GHz using GAMS/CPLEX (v 9.0). From the computational results, shown in Table 4, one can see that this case originates a large model, where 37% of the total variables are binary. The number of constraints is about 20% greater than the number of total variables. Irrespective of its size, it reaches optimality in about two hours. Note that, since we are dealing with a strategic model, the computational times are not critical.

Table 4: Computational results.

Total variables	Binary variables	Total constraints	Optimality margin	Iterations	CPU's (sec.)	Optimal value
121 175	45 012	147 233	0%	690 753	8967	7 853*10^6

As mentioned above two different kinds of decisions are taken: strategic and tactical.

The strategic decision concerns the location of the facilities. This decision is not subjected to scenarios. We aim at establishing a set of facilities that will be able to account for any of the built scenarios. In the optimal solution, Madrid is chosen as the single factory location. This factory serves four warehouses located in Barcelona, Lisboa, Madrid and Porto. In terms of reverse flow, the five given locations were chosen for installing the disassembly centres: Barcelona, Lisboa, Madrid, Malaga and Porto.

The tactical decisions related to production, storage and distribution planning are scenario dependent. For each scenario production, storage and distribution policies are created. The analysis that follows will relate the scenarios within each tactical decision. In the distribution planning, two major analyses will be made: one concerns the flows within the echelons, while the other is related to the total/partial fulfilment of customers' demand and return.

Production plan

Due to the limits imposed on the total production, the optimal policy is found to set the production level to its minimum (0.8*10^6) in scenarios 1 and 2 and to its maximum (1.0*10^6) in scenario 3. This difference is caused by the higher levels of demand that have to be satisfied in the third scenario.

Note that production may take a constant value because the returned products cover the difference between the level of demand and the amount produced

Storage plan

As expected, the optimal storage policy is set to zero, in all scenarios. This is brought about by the cost terms added to the objective function, which act as penalties whenever some stock is created in any kind of facility. The policy is then to minimize inventory costs.

Distribution flows

The analysis made on distribution flows will be split into four parts, each one referring to a different network echelon. The first and second are related with the forward direction of the network and the other two with the reverse network.

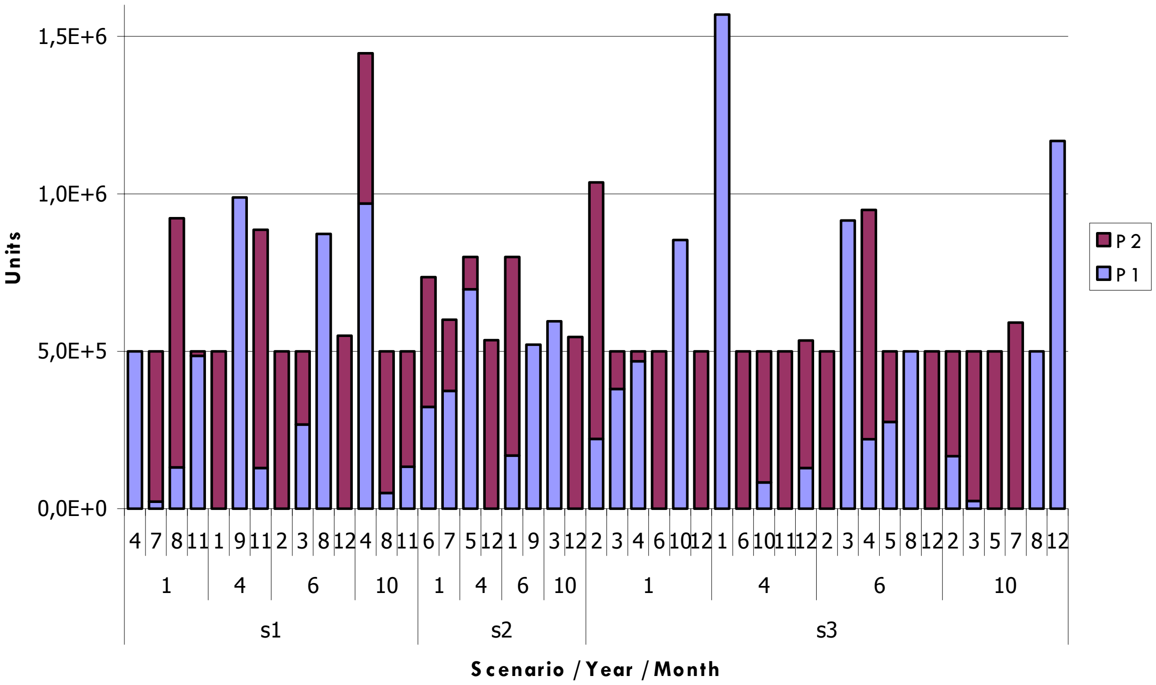

Figure 2: Inbound flows for Porto warehouse.

The first echelon concerns the forward flow between the factory and the warehouses. For each scenario, this flow occurs in every micro time unit, assuring that warehouses will have products to meet customers' demand. In each scenario, the pattern exhibited by the flow is consistent with the existing demand fluctuations.

In Figure 2, the distribution plan between the Porto warehouse and the Madrid factory is shown, covering all flows for the first, fourth, sixth and tenth years, in each of the three scenarios. One can see that flows have a magnitude of at least 500 000 units, which is the lower limit imposed. Note that the observed difference in the number of times the warehouse is supplied, among scenarios, is related to the corresponding demand volumes (the number of flows increases with the demand volume). For the remaining years and warehouses the observed behaviour is identical (not shown).

The second echelon relates warehouses to customers. Every scenario portrays the same policy, differing only in the flow volume and frequency. The connections between each customer and warehouse are shown in Figure 3. Note that although it may seems that Lisboa and Barcelona warehouses are dedicated to just one customer, one should remember that these customers are, in fact, clusters of customers.

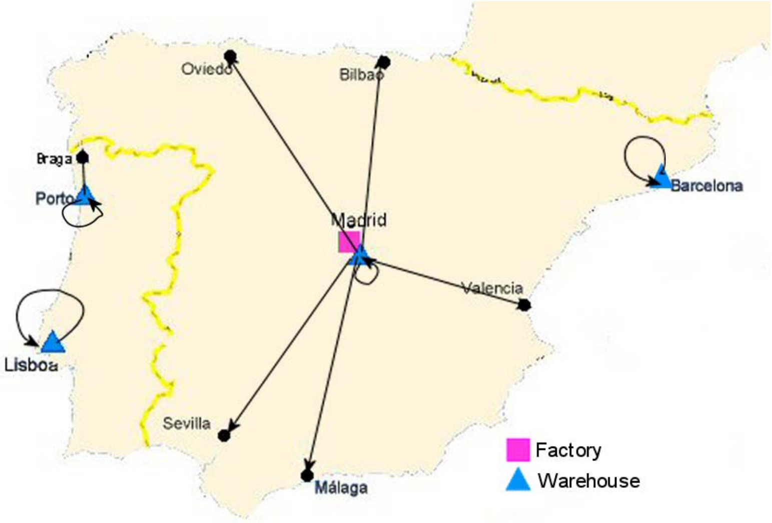

Figure 3: Connections between warehouses and customers.

Each warehouse supplies customers within the same geographical location, and connections between the two countries are kept to a minimum. There is one single and direct link between the Madrid factory and the Portuguese warehouses (not shown in the figure), with no link being established between these and the Spanish customers. The main reason is the tax imposed on flows whenever they connect entities in different countries.

Although scenario dependent, the connection structures resulted equal for all scenarios, which allowed to conclude that the model predicts a robust structure for the forward network.

In terms of the reverse flow, the echelon that links customers to disassembly centres is very alike the one just described. However, some connections have been redirected because one more location, Malaga, was chosen to open a disassembly centre. As shown in Figure 4, this new disassembly centre replaces the previous Madrid connections with one directly between Malaga and Sevilla. Exception made to the connection between Braga and Porto, in scenario 2, this network remains unchanged, in all scenarios, over the time horizon.

Figure 4: Connections between customers and disassembly centres.

Finally, the echelon that links the disassembly centres to the Madrid factory is the one that differs most among the established scenarios. In Figure 5 is presented the total amount of collected product that each disassembly centre, in each scenario, sends either to the Madrid factory (Mdr) for recovery or out of the supply chain for a different treatment (f0).

The most striking feature on this figure is the importance of the centre located in Madrid. This is a direct result of its location since it shares the site with the factory. The observed disparity in the volumes associated to the Madrid centre, is related with the demand and return variability among scenarios. Note that in scenario 2, exception made to the Madrid centre, all other centres send their return to recycling/disposal (f0); one should remember that this is the scenario with the lowest demand and return volumes.

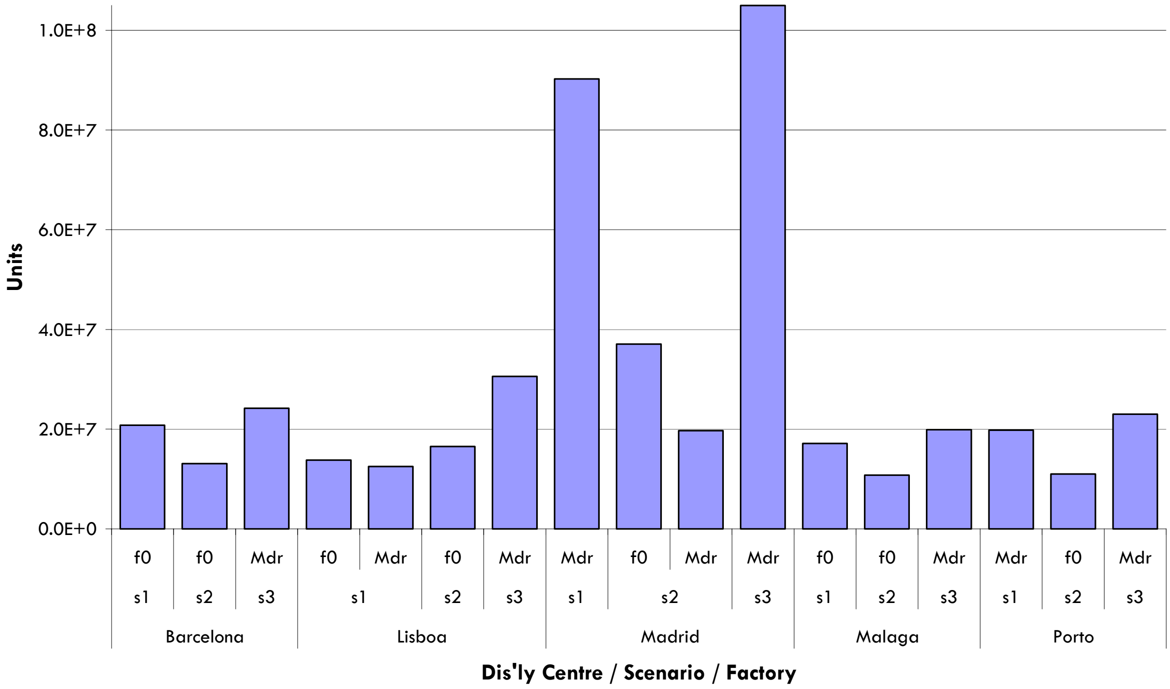

Figure 5: Total outbound flow from disassembly centres, for each scenario.

Another interesting aspect is that the opposite policy is found in scenario 3: all centres send their return to be recovered by the factory (Mdr). Note that this is the scenario with the highest demand and return volumes.

Lastly, for scenario 1, the optimal policy varies from total recovery (Madrid's and Porto's case), to total recycling/disposal (Barcelona's and Malaga's case). Lisboa is an intermediate case, where some products are sent to recovery and some out to disposal.

Non-satisfied demand and return

Demand and return satisfaction is scenario dependent. In scenario 1, all customers have their demand and return fully met. In Scenario 2, however, one customer (Braga) has its demand entirely not satisfied in years 2, 8 and 10, while in all remaining years it is fully satisfied by the Porto warehouse. Still in scenario 2, this same customer never sees its returns collected.

For scenario 3 (Figure 6), one can observe the relationship between customers' supplied (Dmd) and non-supplied demand (Ur). Only three customers have the demand for one of the products not fully supplied: Barcelona, Malaga and Sevilla.

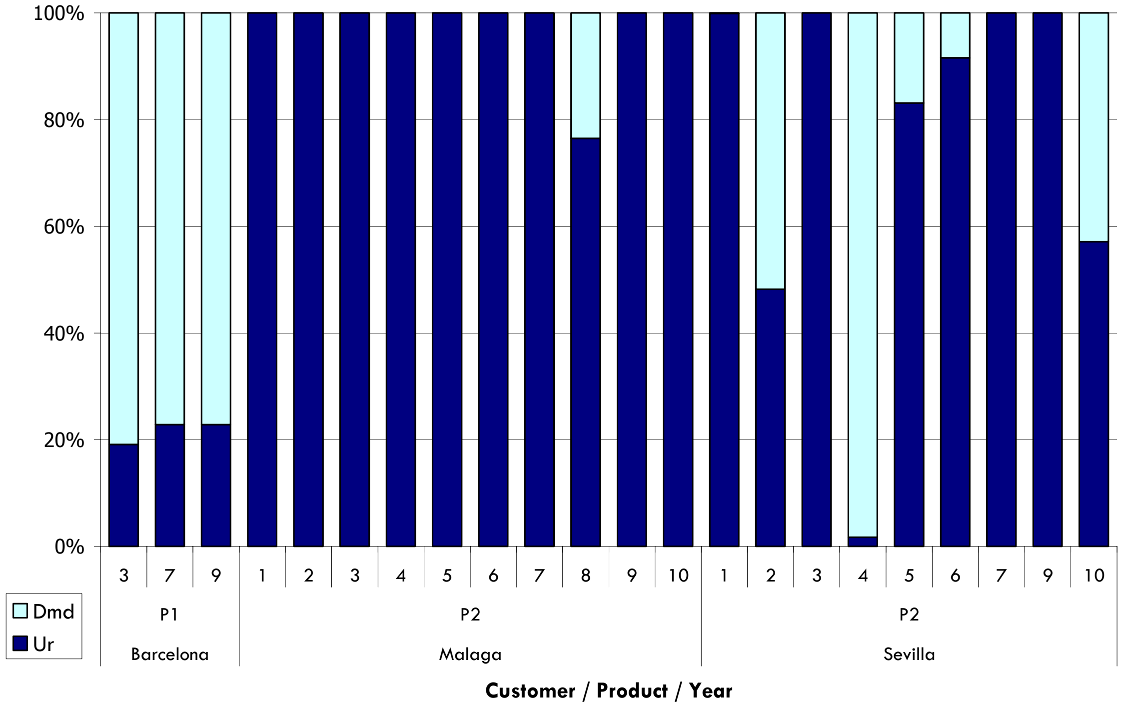

Figure 6: Non-satisfied demand in scenario 3.

Malaga customer receives product P_2 only once. It happens on the eighth year and the supply goes barely beyond 20% of the actual demand. Barcelona customer has its supply reduced by about 20% in three different years, while the supply pattern for the Sevilla customer is quite random.

5 Conclusion

Global supply chains have been given much attention in the past years. Most studies are, however, only concerned with forward chains. Reverse chains are insufficiently covered. Few optimization models addressing either the design of reverse networks or the simultaneous design of forward and reverse networks have been presented.

When considering networks uncertainties, even fewer models have been proposed, when, admittedly, one major source concerns demand and return volumes. In this paper, the presence of uncertainty is explored and demand and return uncertainties are studied using a scenario approach.

A scenario analysis is performed based on a MILP model for the design and planning of an integrated forward and reverse chain, proposed by Salema et al., 2004. While cost is minimized, strategic and tactical decisions are taken over a given time horizon. As strategic decision concerns facility sitting, the chosen sites are scenario independent. On the other hand all tactical decisions are scenario dependent and these concern production, storage and distribution plans for each scenario, over a pre-established planning horizon.

A case study is applied in order to study the model's applicability and adequacy. After a careful result analysis, one can conclude that, although there are some differences between the solutions within each scenario, the general network remains unchanged, rendering a quite stable network design.

The computational results can be considered very satisfactory, considering model size and its strategic nature.

The mathematical formulation which supports the model is, however, likely to increase significantly in complexity with the problem dimension. To overcome this possible computational burden, different solution techniques are now being explored in order to speed up the resolution. Further research is also being undertaken with a view to both strengthen the model formulation and to treat production planning with further detail.

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