UNCERTAIN QUALITY AND QUANTITY OF RETURNS IN A CLOSED-LOOP SUPPLY CHAIN

Luis J Zeballos[a,b*], M Isabel Gomes[c], Ana P Barbosa-Povoa[d], A. Q. Novais[b]
[a]*Unidade Modelação e Optimização de Sistemas Energéticos, Laboratório Nacional de Energia e Geologia, Lisboa*
[b]*Universidad Nacional del Litoral – Fac. de Ingeniería Química, Santa Fe, Argentina.*
[c]*CMA, FCT, Universidade Nova de Lisboa, Monte de Caparica, 2825-114 Caparica, Portugal*
[d]*Centre for Management Studies, Instituto Superior Técnico, Universidade Técnica de Lisboa, Lisboa Portugal*

Abstract

In this work the design and planning of a Closed-Loop Supply Chain (CLSC) under uncertain conditions is considered and a two-stage scenario-based modeling approach is proposed in order to deal with this multi-product, multi-period problem. The network design and tactical plan are simultaneously optimized in a given time horizon, comprehending the raw material acquisition and the processing, storage and distribution of intermediates, returns and final products. Uncertainty is associated to the returns, both in terms of their quantity, which is customer dependent, and quality, which is determined at the sorting centers. Therefore, the ensuing mathematical MILP formulation considers the simultaneous integration of two important uncertainty sources, which represents an important modeling advantage, allowing a better understanding of the reverse network structure. For each probabilistic scenario, the model estimates the amount of products to be returned by customers and of returns to be remanufactured for each quality level, as well as the storage levels. Several tests based on a real sized example of a Portuguese glass company are undertaken in order to show the applicability of the developed approach. Based on these tests, the influence of the uncertain quality and quantity of returns on the design and planning of the CLSC is assessed.

Keywords

Closed-Loop Supply Chain, Design and Planning, Two-stage Stochastic Optimization.

Introduction

The efficient design and planning of Closed-Loop Supply Chains (CLSC) has become an important challenge for many organizations due to a number of reasons: exhaustion of natural resources, increasing environment awareness, regulatory trends, new business opportunities, among others. Thus, not only the efficient study of traditional supply chains that end at final customers, which considers only the forward flow of products (SCFF), is still needed, but more importantly, attention is also required for the CLSC.

From the modeling perspective, the approaches developed for addressing CLSCs should integrate simultaneously processes and constraints that are found in SCFFs and the reverse supply chains. Thus, by comparison with SCFFs, CLSCs further add issues related with the reverse network such as a) product acquisition after the use of customers, b) reverse logistics, c) testing and sorting of products and d) remanufacture or recycle.

An analysis of relevant contributions reveals that a good number of approaches reported in the literature deal with SCFF tactical decisions (Klose and Drexl, 2005; Shah, 2005). In addition, several have been proposed for the design of the reverse supply chains (SC) (for example, le Blanc et al., 2004; Realff et al., 2004), which confirms their importance. However, most of these approaches tend to be case dependent and hence their adaptation to other problems could prove to be hard or inappropriate.

A few works have been published considering simultaneously forward and reverse network structures of

SCs. Some relevant and recent contributions introducing generic CLSC models include Beamon and Fernandes (2004), who developed a model for a single product CLSC design problem in order to analyze the impact of several parameters on the network structure; Lu and Bostel (2007), who proposed an approach for a remanufacturing network, composed of producers, remanufacturing sites, intermediate centers and customers; Salema et al.(2010), who proposed a multi-period, multi-product network model for the simultaneous design and planning of supply chains with reverse flows, where the strategic design of the SC is dealt simultaneously with the tactical decisions related to supply, production, storage and distribution.

The mentioned works address only deterministic aspects of the problem. However, the non consideration of the inherent uncertainty of the global SCs can lead to results of inferior quality and less realistic as compared to formulations where these are explicitly accounted for (Gupta and Maranas, 2003). Most of the relevant and recent works considering the SC design and planning with uncertain parameters are related with forward flow (Azaron et al., 2008; You et al, 2009a,b).

Problem definition

This work addresses the problem of the design and planning of closed-loop supply chains and, hence, the number and location of the different types of network entities should be determined over the complete planning horizon. These entities are factories (F), warehouses (A), customers (C) and sorting centers (R). In addition, the best planning of supply, production, transportation and collection must be determined for every time unit. For the planning two time scales are required: the demand and return values must be satisfied in macro-times (for instance, yearly), while supply, production, transportation and collection values must be determined in micro-times (for instance, monthly).

Some problem features are as follows:

- multiple products flow through the network,
- during the planning horizon, the demand of customers in the network must be partially or totally satisfied,
- new and recycled products are indistinguishable,
- the suppliers of raw materials should deliver products between a maximum and a minimum level imposed by contracts,
- customers return only a fraction of the products supplied, with these return levels being uncertain,
- returns are classified and grouped into several quality grades at the sorting centers, with these quality levels being uncertain and differing in cost,
- maximum and minimum levels of transported products are imposed,
- storage capacities of plants, warehouses and sorting centers have maximum limits,
- sorting centers can only send to disposal a fraction of the collected returns,
- disposal costs are considered for the case of non-recovered returns.

Additional information about most of the stated features can be found in Salema et al. (2010). In addition, due to the presence of multiple uncertainty sources, an important part of the problem is to determine the quantity of returns available to be graded and how much is to be sent to factory or to proper disposal. The next section includes the assumptions adopted for addressing the uncertain quality and quantity of returns.

Formulation

The strategic and tactical CLSC deterministic multi-product multi-period model of Salema et al. (2010) is adopted as the representative approach for the proposed formulation.

To address the uncertainty related with the return levels and the quality of final products, a two-stage stochastic model is introduced. In this approach, the uncertainty is described by a set of discrete scenarios, which denote the way it might operate during the planning horizon subject to the different quality grades and amounts of returns. To each scenario is associated a probability representing its expected occurrence.

While the two-stage scenario-based approach (TSSBA) is presented in this section, the definition of sets, variables and parameters of the model are given at the end of this work. In the proposed formulation, location variables are considered as the first-stage variables, which do not depend on the scenarios outcome, while production, distribution and storage variables are modeled as the second-stage variables. Therefore, the uncertainty in the quality grades and amount of the return flows is translated into the operational decisions through the second-stage variables.

In the TSSBA, the uncertainty on the amount of returns sent by customers to sorting centers is taken into account through R discrete points, each one with a given probability P_r. In addition, the quality of the returns sent to factory is assumed with Q different categories, as a result of the grading process performed in the sorting centers. For example, it is assumed that sorting centers classify the inlet returns according to three different grades: Good, Average and Bad. The quality of returns sent to factory is in turn a combination of these grades in diverse percentages, with an associated uncertainty expressed through G discrete outcomes, each one with a probability P_g. For example, while outcome 1 of the sorting process might be a mix of 30 percent Good, 50 percent Average and 20 percent Bad, outcome 2 might yield 10, 25 and 65, respectively. The applied approach defines a scenario for each combination of the discrete points r and g ($\Omega=\{(r,g)\}$), and therefore, the resulting probability for each one is $P_r P_g$, since both sources of uncertainty are independent.

The objective function of the TSSBA is to minimize the total expected supply chain cost. The performance measure is made up of a) first stage costs and b) expected second stage costs. It is worth noting that each scenario cost is affected by the probability of the scenario.

a) First stage costs:

- cost for opening/use of facilities (first term),
- penalization cost for leaving a customer out of the supply chain. It is proportional to the customer demand (second term).

b) Second stage scenario costs:

- shipment cost proportional to the amount of products transported (third term). In addition, this term also includes the cost related with the acquisition of raw material and the disposal of products,
- cost associated with the graded products that are sent to factory (fourth term). This term adds the costs of the graded products M_r of different qualities flowing from sorting centers I_r to factories I_f (F_{r2}). The cost for each product quality category q is computed by multiplying the amount of returned products ($X_{rgmijt'}$), the fraction of products associated with the quality q ($fr_{gqmijt'}$) and the unit cost of the quality category involved ($cr_{qmijt'}$),
- penalization cost to partially satisfied demand (fifth term),
- penalization cost for any stock left in any entity except at customers (sixth term).

$$Min\ F = \sum_{i \in I} f_i Y_i + \sum_{i \in I_c} c_i d_{mit}(1 - Y_i) + \sum_{(r,g) \in \Omega} P_r P_g \left(\sum_{mij:(m,i,j) \in F \setminus F_{r2}} \sum_{t' \in T'} c_{mijt'} X_{rgmijt'} + \sum_{mij:(m,i,j) \in F_{r2}} \sum_{t' \in T'} \sum_{q \in Q} cr_{qmijt'} fr_{gqmijt'} X_{rgmijt'} + \sum_{mi:(m,i) \in N_c} \sum_{t \in T} c^u_{mit} U_{rgmit} + \sum_{mi:(m,i) \in N \setminus N_c} \sum_{t' \in T'} c^s_{mit} S_{rgmit'} \right) \tag{1}$$

$$S_{rgmi\gamma(t,t'-1)} + \sum_{\bar{m}j:(\bar{m},j,i) \in F} Rf_{r\bar{m}} \beta_{m\bar{m}} X_{rg\bar{m}ji\gamma(t,t'-\tau_{ji}-\phi_m)} = \sum_{\bar{m}j:(\bar{m},i,j) \in F \setminus F_s} Rf_{r\bar{m}} \beta_{m\bar{m}} X_{rg\bar{m}ijt'} + S_{rgmit'} \tag{2}$$
$$(r,g) \in \Omega \wedge (m,i) \in \bar{V} \wedge (t,t') \in \bar{\bar{T}}$$

$$\sum_{j:(m,j,i) \in F} \sum_{t' \in T'} X_{rgmji\gamma(t,t'-\tau_{ji})} + U_{rgmit} = d_{mit} Y_i \tag{3}$$
$$(r,g) \in \Omega \wedge (m,i) \in \breve{V}_c \wedge t \in T$$

$$\sum_{j:(m,i,j) \in F} \sum_{t' \in T'} X_{rgmijt'} + U_{rgmit} = \sum_{\bar{m}j:(\bar{m},j,i) \in F} \sum_{t' \in T'} Rf_{r\bar{m}} \beta_{m\bar{m}} X_{rg\bar{m}ji\gamma(t,t'-\tau_{ji}-\phi_m)} \tag{4}$$
$$(r,g) \in \Omega \wedge (m,i) \in \widehat{V}_c \wedge t \in T$$

$$\sum_{j \in I_0} \sum_{t' \in T'} X_{rgmijt'} \le (1 - \alpha_m) \sum_{\bar{m}j:(\bar{m},j,i) \in F} \sum_{t' \in T'} \beta_{m\bar{m}} X_{rg\bar{m}ji\gamma(t,t'-\tau_{ji})} \tag{5}$$
$$(r,g) \in \Omega \wedge (m,i) \in \widehat{V}_r \wedge t \in T$$

$$\sum_{m:(m,i,j) \in F_s} X_{rgmijt'} \le g^p_j Y_j \tag{6}$$
$$(r,g) \in \Omega \wedge (i,j) \in A_s \wedge (t,t') \in \bar{T}$$

$$\sum_{m:(m,i,j) \in F_s} X_{rgmijt'} \ge h^p_j Y_j \tag{7}$$
$$(r,g) \in \Omega \wedge (i,j) \in A_s \wedge (t,t') \in \bar{T}$$

$$\sum_{m:(m,i) \in N \setminus N_c} S_{rgmit'} \le g^s_i Y_j \tag{8}$$
$$(r,g) \in \Omega \wedge i \in I \wedge (t,t') \in \bar{T}$$

$$\sum_{m:(m,i,j) \in F} X_{rgmijt'} = E_{rgijt'} \tag{9}$$
$$(r,g) \in \Omega \wedge (i,j) \in A \wedge (t,t') \in \bar{T}$$

$$E_{rgijt'} \le BigMY_i \tag{10}$$
$$(r,g) \in \Omega \wedge (i,j) \in A \wedge (t,t') \in \bar{T}$$

$$E_{rgijt'} \le BigMY_j \tag{11}$$
$$(r,g) \in \Omega \wedge (i,j) \in A \wedge (t,t') \in \bar{T}$$

$$\sum_{j:(m,i,j) \in F} X_{rgmijt'} \ge h^c_{mi} Y_i \tag{12}$$
$$(r,g) \in \Omega \wedge (m,i) \in \widehat{V}_c \cup \breve{V}_c \wedge ((t,t') \in \bar{T}: t' \ge \xi_{mi} \vee t \ge t_2)$$

Equations 2-12 are similar to the ones of the deterministic model (Salema et al., 2010). Nevertheless, in the present formulation, constraints are established for each scenario (*r*,*g*). Eq. (2) imposes the material balance for all entities and for the entire set of products. This equation ensures that the inbound flow must equal the outbound flow plus the difference between the existing and the new retained stocks. It is important to note that the discrete return levels at the customers are taken into account through parameter $Rf_{r\bar{m}}$. This corresponds to the return fraction of the final product $\bar{m}$ at level *r*. Eq. (3) enforces the demand satisfaction. Eq. (4) guarantees customer returns. The total quantity of returned products available at each customer depends on the supplied amount and the return fraction of the final product $\bar{m}$ at return level *r*. Constraint (5) imposes the legislation targets for the recovering of materials. Constraints (6) and (7) model maximum and minimum limits for supplied volumes. Constraint (8) limits the storage capacity in factories, warehouses and sorting centers. Constraints (9)–(11) are the flow constraints between two different entities. Finally, constraint (12) ensures that a minimum flow must reach and leave each customer.

Case Study

The applicability of the approach is shown through the solution of an example based on the case study of a Portuguese glass company (Salema et al., 2010). Instances of the example are solved in order to investigate the impact on the CLSC when changes in parameters associated with the quality and quantity of the return flows are performed.

In this work, while the recovery target (α) is assumed as a deterministic parameter, with a value of 0.80, the uncertain quality of returns sent to factory is approximated by five possible outcomes: *Best(g1)*, *Better(g2)*, *Average(g3)*, *Worse(g4)* and *Worst(g5)*. Each outcome is in turn a mix of the three quality grades, called *Good*, *Medium* and *Bad*, resulting of the classification process at the sorting centres. Outcomes and grading levels are taken as suggested in (Denizel et al., 2010) for the remanufacturing planning of semiconductors. Table 1 shows the occurrence probability of each outcome and the percentage of return products of each quality grade. As it can be seen, the *Better* category assumes that 66.7 percent of the graded products are Good, 33.3 percent are Medium and 0 percent are Bad.

Table 1. Grading Levels for the returned products

Grading outcomes	Prob	% Good	% Medium	% Bad
Best (g1)	0.05	1	0	0
Better (g2)	0.20	66.7	33.3	0
Average (g3)	0.50	33.3	33.3	33.4
Worse (g4)	0.15	0	33.3	66.7
Worst (g5)	0.10	0	0	1

Returns from customers (white and non-white glass, designated C2 and C1) are classified at the sorting centers before being sent to factories. Since the returned products compete with raw materials by being integrated into the processing of new products, their composition and cost are critical system parameters. Table 2 completes the problem data by showing the raw material and graded product prices in arbitrary currency units (c.u.).

Table 2. Raw material and graded product prices

		Unit product price	
		C1	C2
Raw Material		0.045	0.060
Graded Products	*Good*	0.010	0.005
	Medium	0.045	0.060
	Bad	0.080	0.115

The uncertain quantity of products returned by customers is approximated by three possible return levels: *Optimistic (r1), Moderate (r2)* and *Pessimistic (r3).* Table 3 shows the customers' return fractions of final products and the occurrence probability of each level.

Table 3. Customers' return fraction of final products

	Return Levels	Prob	Final Products					
			A1	A2	A3	A4	A5	A6
Return Fractions	*Optimistic (r1)*	0.35	0.55	0.80	0.60	0.90	0.50	0.99
	Moderate (r2)	0.45	0.45	0.70	0.50	0.80	0.40	0.90
	Pessimistic(r3)	0.20	0.35	0.60	0.40	0.70	0.30	0.80

Numerical Results

The mathematical formulation was implemented in GAMS 23.6.3 and solved with CPLEX 12.2, on a laptop with Intel Core i7 Q740 1.73GHz and 8 GB RAM memory for a 0.001% gap tolerance.

To illustrate the effects of uncertainty, nine different cases have been solved. Five of these show the effects of the different outcomes considered (*Best, Better, Average, Worse* and *Worst*) when the three possible return levels are simultaneously taken into account. Three cases are associated with the customers' return levels when the five outcomes are considered altogether. Finally, the ninth case is the stochastic instance (ST) with 15 possible scenarios. The results are depicted in Table 4.

As can be seen from rows 2 to 6 of Table 4, the quality of the returned products to factory assumes a great importance when minimizing the network cost. Thus, the more extended network structure (3 factories, 3 warehouses, 17 costumers and 2 sorting centres) with the smallest cost is obtained considering that 100% of the returned products are of Good quality. The network size decreases as the quality declines, reaching its minimum (2 factories, 2 warehouses, 6 costumers and 2 sorting centres) for case g4-(r1-r3). From case g1-(r1-r3) to g3-(r1-r3) the network structure only suffers modifications on the number of customers (C). In addition, it is worth remarking that from case g4-(r1-r3) downwards the network configuration is significantly modified.

Table 4. Optimal network results

Cases	Min F [c,u,]	Network structure*				Total number of entities
		F	A	C	S	
g1-(r1-r3)	6226.85	3	3	17	2	25
g2-(r1-r3)	7228.84	3	3	16	2	24
g3-(r1-r3)	8618.89	3	3	12	2	20
g4-(r1-r3)	9579.13	2	2	6	2	12
g5-(r1-r3)	9909.47	2	2	7	2	13
r1-(g1-g5)	8863.10	3	3	18	2	26
r2-(g1-g5)	8481.12	3	3	16	2	24
r3-(g1-g5)	8287.83	3	3	12	2	20
ST	8588.49	3	3	13	2	21

*F – factories; A – warehouses; C- Costumers; S – Sorting Centres

While this is the case for the network structure for instances g1-(r1-r3) to g5-(r1-r3), it is important to notice that the objective function values increase mainly due to the loss of customers and rearrangements in the flow levels of products and, therefore, in the cost composition of the objective function. Figure 1 shows the flows between: Suppliers to Factories (F), Customers to Sorting Centres (C-S), Customers to Disposal (C-D), Sorting Centres to Factories (S-F), as well as Sorting Centres to Disposal (S-D), for the different return qualities.

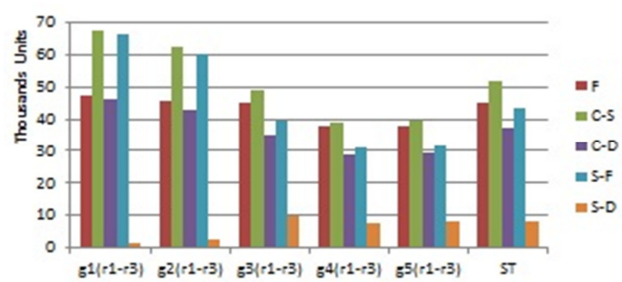

Figure 1. Resulting flows of the different return qualities

The solution of instance ST, by comparison with cases g1-(r1-r3) to g5-(r1-r3), is found to be similar to g3-(r1-r3) in number of entities and the flow levels. While in case ST 13 customers are served, in instance g3-(r1-r3) only 12 integrate the network. In addition, case ST has, on average, flows greater than instance g3-(r1-r3). Considering the disposal volume in the sorting centers (S-D), case ST assumes a recovery level of 84,23 %, that is greater than the 80% legal target. On the contrary, for cases g4-(r1-r3) and g5-(r1-r3) the disposal volume is at its allowed maximum.

The effect of changes on the amount of final products returned by customers to sorting centres is shown in Figure 2. Given the graded products prices (see Table 2) when the return quantities decrease, the number of entities in the network decreases and the objective function value also decreases. While the number of factories, warehouses and grading centres are equal for the three return levels, the number of customers varies (18 for the Optimistic case, 16 for the Moderate and 12 for the Pessimistic).

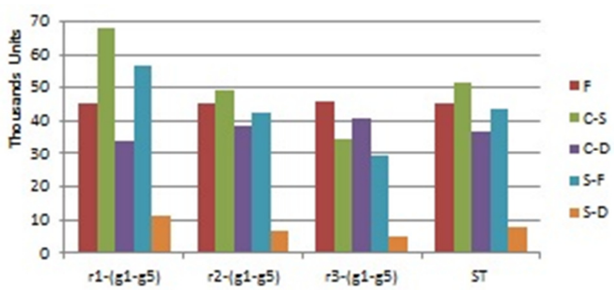

Figure 2. Resulting flows of the different return fractions

As it can be observed in Figure 2, while the raw material requirements (F) are almost the same for cases r1-(g1-g5) to r3-(g1-g5), the flow of salvaged products markedly decreases due to the reduction in the return levels. Furthermore, it is important to notice that in instance r3-(g1-g5), the raw material requirements markedly exceeds the flow of returned products. Thus, the drop in the number of customers is mainly caused by the flow reduction of returned products.

Table 5 shows the computational statistics for the cases solved. Given that the model dimensions for similar types of instances are the same, these are grouped and only the average computational effort is reported.

Table 5. Computational statistics

Cases	Variables			Constraints	CPU [min]
	Total	Binary	Semi-continuous		
g1-g5-(r1-r3)	33168	38	33120	123939	2041
r1-r3-(g1-g5)	55200	38	55162	206540	2672
ST	165638	38	165600	619695	4580

As it can be seen from this table, the model is found to be extremely intensive computationally. From a problem-solving point of view, it represents a considerable challenge because the model size (in term of number of variables and constraints) increases with the number of scenarios.

Conclusions

In this paper, a two-stage scenario-based approach was proposed for incorporating the uncertainty in the quality and quantity of returned products in the design and planning problem of CLSCs. The formulation therefore considers the simultaneous integration of two important uncertainty sources, which represents an important modeling advantage of the proposed approach, allowing a better understanding of the characteristics of the reverse network. Thus, the flows of products sent by customers to sorting centers and the flows of recycled as well as of non-conformed products (sent to factories for reprocessing or to disposal, respectively) can be analyzed under different uncertain situations.

The formulation relevance was evaluated by an example based on an industrial case that involves the CLSC of a Portuguese glass firm. Through the numerical tests obtained with the proposed approach for the different cases, the relative impact of the uncertainty on the structure, planning and cost of the CLSC were analyzed. From the results obtained with cases g1-(r1-r3) to g5-(r1-r3), and r1-(g1-g5) to r3-(g1-g5), interesting insights could be obtained. For example, while the return quality has an important effect on the total expected supply chain cost and network structure, the amount of returned products has a much narrower impact. In addition, the ST instance allowed the determination of the most adequate network, when the uncertain quality and quality of the returns are simultaneously considered.

As future work, the extension of the approach to account for a more general representation of the probability distributions will be pursued, together with the development of a specialized algorithm exploiting the problem structure to provide solutions in reasonable computational time.

Acknowledgments

The authors gratefully acknowledge the support of the Portuguese National Science Foundation through the project PTDC/SEN-ENR/102869/2008 and research grant SFRH/BPD/69279/2010; also partial support through CMA/FCT/UNL, under “Financiamento Base 2009 ISFL-1-297” from FCT/MCTES/PT, is also acknowledged.

Appendix A

Sets

Entities:

I_f possible locations for factories, I_a possible locations for warehouses, I_c locations of customers, I_r possible locations for disassembly centres, I_0 disposal option

Products:

Mf factories outbound products, Ma warehouses outbound products, Mc customers outbound products, Mr disassembly centers outbound products.

Scenarios:

R return levels of final products, $r\epsilon R$,

G outcomes of the grading process (grading outcomes), $g\epsilon G$,

Q quality categories of products obtained as result of sorting centers operations, $q\epsilon Q$,

$\Omega = \{(r,g): r \in R \ \wedge g \in G\}$,

Products-entities:

$\check{V}_f = \{(m,i): m \in M_f \ \wedge i \in I_f\}$, $\check{V}_a = \{(m,i): m \in M_a \ \wedge i \in I_a\}$

$\check{V}_c = \{(m,i): m \in M_c \ \wedge i \in I_c\}$, $\check{V}_r = \{(m,i): m \in M_r \ \wedge i \in I_r\}$,

$\hat{V}_f = \{(m,i): m \in M_r \ \wedge i \in I_f\}$, $\hat{V}_c = \{(m,i): m \in M_a \ \wedge i \in I_c\}$,

$\bar{V} = \hat{V}_f \cup \check{V}_a \cup \check{V}_r \cup \check{V}_c$.

Flows:

$A_{f1} = \{(i,j): i \in I_f \ \wedge j \in I_a\}$, $A_{f2} = \{(i,j): i \in I_a \ \wedge j \in I_c\}$,

$A_{r1} = \{(i,j): i \in I_c \ \wedge j \in I_r\}$, $A_{r2} = \{(i,j): i \in I_r \ \wedge j \in I_f\}$,

$A_s = \{(i,i): i \in I_f\}$, $A_d = \{(i,j): i \in I_r \ \wedge j \in I_0\}$.

Time

T macro-times,

T` micro-times,

$\bar{T} = \{(t,t`): t \in T \ \wedge t` \in T`\}$ *all time units,*

Products-Flows:

$F_{f1} = \{(m,i,j): m \in M_f \ \wedge (i,j) \in A_{f1}\}$,

$F_{f2} = \{(m,i,j): m \in M_a \ \wedge (i,j) \in A_{f2}\}$,

$F_{r1} = \{(m,i,j): m \in M_r \ \wedge (i,j) \in A_{r1}\}$,

$F_{r2} = \{(m,i,j): m \in M_c \ \wedge (i,j) \in A_{r2}\}$,

$F_s = \{(m,i,j): m \in M_c \ \wedge (i,j) \in A_s\}$,

$F_d = \{(m,i,j): m \in M_c \ \wedge (i,j) \in A_d\}$.

Parameters

τ_{ij} travel time between entities *i* and *j*,

ϕ_m processing/usage time of product *m*,

$\xi_{mi} = f(\tau_{ij}, \phi_m)$ function of both travel and processing times, giving the earliest micro-time unit a flow of product $m\epsilon M$, with origin in entity $i\epsilon I$, may occur.

α_m recovery target for product *m* set by legislation, $\alpha_m\epsilon[0,1]$,

$\beta_{m\bar{m}}$ relation between product m and $\bar{m}$,

s_{mi0} initial stock of product m in entity $i\epsilon I$,

f_i investment cost of entity $i\epsilon I$,

c_i cost of leaving customer *i* out of the supply chain,

g_i^s maximum storage capacity of entity $i\epsilon I$,

g_i^p and h_i^p maximum and minimum supplying limit of entity $i\epsilon I_f$,

g_{ij} upper bound value for flows connecting entities *i* and *j*,

h_{ij} lower bound value for flows connecting entities *i* and *j*,

h_{mi}^c lower bound value of product *m* flow leaving entity $i\epsilon I_c$.

$cr_{qmijt`}$ unit cost of quality category *q* of returned product *m* from entity *i* to entity *j*, at time *t`*,

$fr_{gqmijt`}$ fraction of quality *q* of grading category *g* of product *m* from entity $i\epsilon I_r$, to entity $j\epsilon I_f$, at time *t`*,

Rf_{rm} return fraction of final product $m\epsilon M_c$ at level *r*. This parameter adopts the value one when $m \notin M_c$,

P_g occurrence probability of the grading outcome *g*,

P_r occurrence probability of the return level *r*,

Macro-time parameters

d_{mit} product *m* demand for entity *i* for macro-period *t*, $i\epsilon I_c$,

c_{mit}^u unit variable cost of non-satisfied demand/return of product *m* to entity $i\epsilon I_c$, for macro-period t.

Microtime parameters

$c_{mijt`}$ unit transportation cost of product *m* from entity *i* to entity *j*, at time *t`*,

$c_{mit`}^s$ unit storage cost at entity *i*, at time *t`*.

Continuous Variables

$X_{rgmijt`}$ amount of product *m* transported from entity *i* to entity *j*, at micro-time *t`*, at scenario *(r,g)* corresponding to return level *r* and grading outcome *g*

$S_{rgmit`}$ amount of product *m* stored in entity *i*, at micro-period *t`*, at scenario *(r,g)*

U_{rgmit} non-satisfied amount of product *m* in customer *i*, over macro-period *t*, at scenario *(r,g),*

Binary variables

Y_i entity *i* opened/served,

Semi-continuous variable

$E_{rgijt`}$ limits the maximum and minimum amount of products that flow between entities *i* and *j*, at micro-time *t`*, for each scenario *(r,g)*. These variables can either be 0, or can behave as continuous variables between lower bound and upper bound values for flows connecting entities *i* and *j* $[h_{ij}, g_{ij}]$.

References

Azaron, A., Brown, K.N., Tarim, S.A., Modarres, M. (2008). A multi-objective stochastic programming approach for supply chain design considering risk International *Journal of Production Economics*, 116(1), 129-138.

Beamon, B.M., Fernandes, C. (2004). Supply-chain network configuration for product recovery. *Production, Planning and Control*, 15 (3), 270–281.

Gupta, A., Maranas, C.D. (2003). Managing demand uncertainty in supply chain planning. *Comput. Chem. Eng.*, 27 (8-9), 1219-1227.

Klose, A., Drexl, A. (2005). Facility location models for distribution system design. *European Journal of Operational Research*, 162 (1), 4–29.

le Blanc, H.M., Fleuren, H.A., Krikke, H.R. (2004). Redesign of a recycling system for LPG-tanks. *OR Spectrum*, 26 (2), 283–304.

Lu, Z.Q., Bostel, N. (2007). A facility location model for logistics systems including reverse flows: The case of remanufacturing activities. *Computer & Operations Research*, 34 (2), 299–323.

Denizel, M.; Ferguson, M.; Souza, G. (2010). Multiperiod Remanufacturing Planning With Uncertain Quality of Inputs. *IEEE Transactions on Engineering Management*, 57 (3), 394 – 404.

Realff, M.J., Ammons, J.C., Newton, D.J. (2004). Robust reverse production system design for carpet recycling. *IIE Transactions*, 36 (8), 767–776.

Salema, M.I.G., Barbosa-Povoa, A.P., and Novais, A.Q. (2010). Simultaneous design and planning of supply chains with reverse flows: A generic modeling framework. *European Journal of Operational Research*, 203(2), 336-349.

Shah, N. (2005). Process industry supply chains: Advances and challenges. *Comput. Chem. Eng.*, 29 (6), 1225–1235.

You, F., Wassick, J.M., Grossmann, I.E. (2009). Risk Management for a Global Supply Chain Planning under Uncertainty: Models and Algorithms. *AIChE Journal*, 55, 931-946.

You, F., Grossmann, I. E., and Jacek Jezowski and Jan, T. (2009). Optimal Design of Large-Scale Supply Chain with Multi-Echelon Inventory and Risk Pooling under Demand Uncertainty. *Computer Aided Chemical Engineering*, 26, 991-996.