# PRODUCT AND CLOSED-LOOP SUPPLY CHAIN DESIGN WITH UNCERTAIN RETURN FLOWS

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*Abstract*

This paper addresses the product and network design for a multi-product, multi-echelon and multi-period closed-loop supply chain (CLSC). Decisions associated with the products to manufacturing (new and remanufactured) and their associated raw materials (new and recovered) are simultaneously considered with the network design. The network superstructure includes two types of customers (first and second markets), raw material suppliers, factories, distribution centers, customer demands, recovery centers, recycle centers, final disposal locations and re-distribution centers. Uncertain quality and quantity of the return flows are considered. Risk management related to critical uncertain parameters is performed.

A two-stage stochastic linear programming approach is developed to explore and exploit network improvements by using risk management in the product and network design problem. The model objective function is based on the conditional value at risk (CVaR) concept applied to the profits. The formulation aims to find feasible solutions with high economic and environmental benefits while managing raw materials, products, return flows and network structure. A case study from a European consumer goods company is employed in order to show the effectiveness of the approach.

*Keywords*

Mathematical modeling, stochastic approach, product design, closed-loop supply chain.

## Introduction

Nowadays, organizations that manufacture new products require to consider several factors related to the environmental impact of their products, including government regulations, consumer preferences, and corporate environmental objectives (Fitzgerald et al, 2007). The environmental impact generated by a product can be reduced through different ways. However, many authors (Handfield et al., 2001, Fiksel, 1996 and Bras, 1997) emphasize that the greatest opportunity arises in the stages of product design. Therefore, given the significance of the product design, it is highly desirable the incorporation of the decisions of product design along with strategic, tactical and operational decisions of CLSCs. CLSCs are focused on taking back products from customers and recovering added value by reusing the entire product, some parts or raw materials in order to exploit the economic potential given by the flow of product returned by customers.

The consideration of uncertain parameters in supply chain and operations management has been widely recognized as a relevant issue. Customers' demands, supply levels, return flows (quantity and quality of returned products) are critical factors with quite uncertain values in the supply chain context. In addition, the relationship between product design and CLSC design and management is strongly affected by the business environment changes. For example, product and network design problems in a CLSC context are strategic topics that require to take into account future circumstances of the business environment as opening network entities with certain capabilities and capacities are a long and expensive process. Therefore, given the previous mentioned issues, it is important to note that the use of stochastic programming techniques is unavoidable for SCM (Supply Chain Management) (Barbosa-Póvoa, 2014).

Considering the design and planning of CLSCs with uncertain parameters, it can be mentioned the following papers: Cardoso et al (2013); Zeballos et al. (2014) as well as Khatami et al. (2015). However, the above works propose formulations where the effects of the variability of random events are not taken into account. Few works include contributions related to risk averse formulations (e.g. Soleimani et al., 2014 and Subulan et al., 2015). Additionally, despite the importance of coordinating product design and SC design, the works mentioned in the last paragraph do not consider this issue. Some of the early papers addressing product design and SC structure are focused on the integration of supplier's activities as part of the network and not in the entire CLSC (Krikke et al., 2003; Fixson 2004). A more recent contribution, Metta and Badurdeen (2013), proposes a formulation with the objective of evaluating supply chain (SC) configurations along with product designs. The approach addresses the problem by parts (hierarchical formulation) and does not take into account the existence of uncertain conditions. Thus, there is a need of addressing the coordinated SC design and product design in CLSC decisions.

**Problem Description**

This work addresses the product and network design for a multi-echelon CLSC consisting of a set of raw material suppliers, factories, distribution centers, customer demands, recovery centers, recycle centers, final disposal locations and re-distribution centers (see Figure 1). Demands are connected with customers that must be satisfied with new products (first market) and remanufactured products in good working conditions (second market). Uncertain quality and quantity of return flows are considered. Final products are produced using a variety of raw materials and manufacturing resources. Several alternative designs for the same set of final products are considered, and from these only one design is allowed for the full CLSC. The final products obtained with any of the alternative designs are equal in quality and functionality terms. Independently of the design, all final products are obtained using the same group of raw materials. The raw materials requirements depend on the design and it is important to remark that each product design leads to different handling and processing of the products after they are discarded by customers.

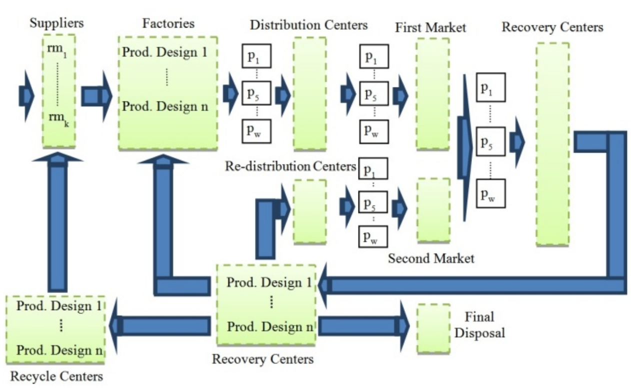


*Figure 1. CLSC structure and Schematic representation of product flows*

In this work, the design for remanufacturing (DfRm) and the design for recycling (DfRc) are considered as opposed designs. DfRm pays attention to recover, check, and utilize modules, parts, components of final products discarded by customers in the same or different products. DfRc focuses on facilitating the recycling of raw materials during the entire product life-cycle. In addition, another alternative designs that lead to different levels of remanufacturing and recycling are also considered as part of the problem. The alternative designs adopt philosophies of design that are between the principles of DfRm and DfRc. The following assumptions associated with the product designs are considered: DfRm is associated with tasks performed predominantly by trained employees; and DfRc is connected to activities based on automatic equipment involving mechanical and/or chemical recovery of raw materials. The remanufacturing activities, such as inspection, disassemble, replace and/or repair parts, modules or products, are tasks performed by skilled employees at relatively low rates of processing. Nevertheless, these activities lead to products for secondary markets with significant sales gains (Ilgın and Gupta, 2012). On the other hand, as mentioned the recycling activities are associated with mechanical and/or chemical processes that can be performed automatically. Thus, these activities are carried out with high raw materials recovery rates and at low costs. However, the economic benefit of carrying out raw materials recovery is limited (Ilgın and Gupta, 2012). Therefore, in this work, it is considered that the product designs directly influence the fixed costs as they affect mainly the capabilities and capacities of reverse network entities (such as recovery and recycle centers). In addition, the product designs determine the flow of products between different network entities, mainly those entities belonging to the reverse network, due to the different remanufacturing/recycling rates. Thus, products discarded by end users flow through the reverse network at different rates, depending on their origin and destination. In addition, to show the different types of entities considered as part of the CLSC, Figure 1 shows the entities affected by the alternative product designs. Moreover, Figure 1 shows a schematic representation of raw materials (*rm*) and final products (*p*) flows in the CLSC.

Other problem features are: a) the planning horizon is divided into several time periods, b) capacities and locations of the entities that can be included on the CLSC are known in advance, c) new and remanufactured products are differentiated for customers, d) the amount of space between entities and transportation capacities are known and fixed, e) the unit costs of purchasing, inventory, transportation and CO2 emissions are known in advance, f) not all products sold are recovered after their useful life, g) material flow connections between entities of the same type are allowed and g) maximum and minimum capacities for inventory, production and transportation are considered.

Finally, the objective is to maximize the overall profit of the network in order to determine the optimal coordination between alternative product designs and the CLSC configuration.

**Problem Formulation**

A stochastic MILP model is formulated where the set of final products must be produced according to a unique product design selected between all possible designs in a CLSC context. Thus, the model addresses the coordination between the product designs and the CLSC configuration under uncertain conditions related to the quality and quantity of return flows. The optimization problem consists of a profit maximization objective function and constraints for CLSC structure, transportation, material supply, final products flows, production, resources, products demand and inventory capacity.

A two-stage stochastic approach is employed to deal with the uncertain parameters. The risk management is also addressed. The popular function for managing variability and risk, called CVaR, is considered in the model performance measure. The objective function incorporates terms that explicitly quantify the variability and the risk associated with the profit. To the best of our knowledge, this work is one of the first attempts in using a two-stage stochastic approach for dealing with the uncertainty of the quality and quantity of return flows, and considering the CVaR as risk measure in a CLSC with the comprehensive consideration of the problems of product and network design.

In the proposed approach it is assumed that the quality and quantity of the return flows are represented by a finite number of scenarios with certain probability each one. The model uses a two-layered scenario tree, where each tree node is associated with the individual effects of the two independent random parameters. Since an approach with only two layers is considered, after the occurrence of the events in the first planning period, the adopted levels of quality and quantity of return flows continue in the same values during the entire planning horizon.

In the proposed formulation, variables associated with the selection of a given product design for the network and entities location variables are modeled as the first-stage since these do not depend on the scenarios conditions. In addition, these variables are to be determined before uncertain parameters are considered. Production, handling, distribution and storage variables are the second-stage variables since these are determined in the face of uncertainty. It is worth noting that the selected product design affects the production cost and the rate of production of several entities. Thus, the selection of the most suitable entities for recovery, redistributions, recycle and final disposal centers depends on the product design. Network entities are characterized by the costs of installation, processing, storage and handling, as well as the maximum and minimum capacities of processing and storage.

The formulation includes constraints associated with: opening of network entities, selection of a given product design; maximum and minimum bounds for the raw material supply; demand of first market; minimum value of the second market demand; the material balance at each entity; the maximum and minimum transportation capacity between two entities; the minimum storage level in the network entities; maximum bounds for the use of manufacturing resources; the minimum and maximum processing capacity in factories; the existence of incoming and outgoing transport movements. It is important to note that processing and storage of the reverse network entities depend on the product design. In addition, the ratio of recycling, repairing, remanufacturing and disposing depend on the product design and the quality and quantity of the returns considered in each scenario. Thus, these issues are taken into account in the respective constraints.

Unfortunately, due to space limits, only important constraints related to the product design and uncertain parameters are shown. Complementary constraints can be deduced from related paper such as Kalaitzidou et all. (2015) and Zeballos et all. (2014).

The objective function (Equation 1) regards the expected revenues and costs as well as a term to measure the risk. This risk measure is accounted in the last term, which is affected by a non-negative weighted factor ($\lambda$), that is a trade-off coefficient representing the relationship between the risk and the expected values of revenues and costs. *ER* characterizes the expected revenues achieved by selling new and recycled products and the revenues obtained by introducing recovered materials into the forward network for all scenarios $s$ considered. *EOC* represents the expected operational costs associated with handling, production, transportation and $CO_2$ emissions of the forward and reverse chains. In addition, the purchasing costs of raw material transported from suppliers to plants and the storage costs are also considered in term *EOC*. *SCSC* symbolizes the cost for opening facilities at the beginning of the planning horizon. Finally, the last term of equation (1) is the application of the CVaR concept to the profit. This risk measure, called CVaRp, is used to reduce the likelihood that the product and network designs incur in large decreases in profit when uncertain events occur. Thus, the risk measure denotes the practical implementation of CVaR concept in order to penalize the decreasing of profit below a given value imposed by the confidence level ($1\text{-}\alpha p$). In addition, constraint (2) determines the difference between a given level of expected profit ($\eta p$) and the profit of the scenarios that are outside of the confidence interval. $\eta p$ is determined during the optimization process in function of the selected confidence level. The deviational variable $dv\eta p_s$ is greater than zero when the difference between the revenues of scenario $s \epsilon SC$ ($R_s$) less the operational cost of the same scenario $s$ ($OC_s$) is less than $\eta p$. The variable $dv\eta p_s$ quantifies the reduction of profit of the scenario $s$ when its profits are less than $\eta p$. It is important to note that in the risk measure, when considering large confidence levels (small values of $\alpha p$) more scenarios are considered and thus the solution becomes more averse to incurring in large decreases in profit for certain scenarios. It is worth remarking that the complement of the parameter $\alpha p$ is the confidence level ($1\text{-}\alpha p$).

Constraint (3) imposes the condition that only one product design must be selected. $yd_d$ is a binary variable that adopts value 1 when the product design $d \epsilon D$ is selected. Constraint (4) allows the production of certain final products according to the design selected. $p_{diptn}$ is the rate of production of final product $p \epsilon P^{fp}$ considering the product design $d$ at plant $i$ belonging to the set of plants $I_f$

during time period $t\epsilon T$ at node $n\epsilon\{NT_t \cap NS_s\}$. $NS_s$ and $NT_t$ are the set of nodes belonging to the scenario *s* and the set of nodes associated with time period *t*, respectively.

$$\text{CVaRp}: ER - EOC - (1+\lambda)\, SCSC + \lambda\left[\eta p - \frac{1}{(1-\alpha p)}\sum_{s\epsilon SC}[Pb_s(dv\eta p_s)]\right] \quad (1)$$

$$(R_s - OC_s) - \eta p + dv\eta p_s \geq 0 \qquad \forall s \in SC \quad (2)$$

$$\sum_{d\epsilon D} yd_d = 1 \quad (3)$$

$$\sum_{d'\epsilon D, d'\neq d}\sum_{i\epsilon I_f}\sum_{p\epsilon P^{fp}}\sum_{t\epsilon T}\sum_{n\epsilon\{NS_s \cap NT_t\}} p_{d'iptn} \leq M(1-yd_d) \qquad \forall\, d\epsilon D \quad (4)$$

$$p_{diptn} \geq -M(1-yd_d) + y_i P_{pid}^{min} \quad (5)$$
$$\forall\, d\epsilon D, \forall\, i\epsilon I_f, \forall\, p\epsilon P^{fp}, \forall t\epsilon T, \forall\, s\epsilon SC, \forall\, n\,\epsilon\{NT_t \cap NS_s\}$$

$$p_{diptn} \leq M(1-yd_d) + y_i P_{pid}^{max} \quad (6)$$
$$\forall\, d\epsilon D, \forall\, i\epsilon I_f, \forall\, p\epsilon P^{fp}, \forall t\epsilon T, \forall\, s\epsilon SC, \forall\, n\,\epsilon\{NT_t \cap NS_s\}$$

$$vCRe_i \geq y_i C_{id}^{Re} - M(1-yd_d) \qquad \forall\, d\epsilon D, \forall\, i\epsilon I_{rcc} \quad (7)$$

$$vCR_i \geq y_i C_{id}^{R} - M(1-yd_d) \qquad \forall\, d\epsilon D, \forall\, i\epsilon I_{rc} \quad (8)$$

$$\sum_{j\epsilon I_{rc}} q_{ijptn} = \sum_{j\epsilon I_{dc}} q_{jiptn} \sum_{uqt\epsilon EQT_n} RC_{uqt} \quad (9)$$
$$\forall\, d\epsilon D, \forall\, i\epsilon I_{fm}, \forall\, p\epsilon P^{rm}, \forall t\epsilon T, \forall\, s\epsilon SC, \forall\, n\,\epsilon\{NT_t \cap NS_s\}$$

$$\sum_{j\epsilon I_{rcc}} q_{ijptn} \geq \left(\sum_{j\epsilon I_{rcc}} q_{ijptn} + \sum_{j\epsilon I_{rdc}} q_{ijptn} + \sum_{j\epsilon I_{fd}} q_{ijptn} + \sum_{j\epsilon I_f} q_{ijptn} - \sum_{j\epsilon I_{rc}\, j\neq i} q_{ijptn}\right) * \sum_{uql\epsilon EQL_n} RRe_{duql} - M(1-yd_d) \quad (10)$$
$$\forall\, d\epsilon D, \forall\, i\epsilon I_{rc}, \forall\, p\epsilon P^{fp}, \forall t\epsilon T, \forall\, s\epsilon SC, \forall\, n\,\epsilon\{NT_t \cap NS_s\}$$

Constraints (5) and (6) bound the minimum and maximum production capacity rates. $P_{pid}^{min}$ and $P_{pid}^{max}$ are the minimum and maximum production capacities of final product *p* of production plant *i* considering the product design *d*. Constraints (7) and (8) compute the costs of establishing recycle centers ($i\epsilon I_{rcc}$) and recovery centers ($i\epsilon I_{rc}$) considering a given product design. $vCR_i$ and $vCRe_i$ are continuous variables used to determine the costs of establishing entities depending on the facility and the product design. $C_{id}^{R}$ and $C_{id}^{Re}$ are fixed costs of establishing recovery and recycle centers, respectively. Constraint (9) establishes that the flow of recoverable material exiting from the first market to recovery centers is equal to the flows that enter to the first market multiplied by a return ratio. $RC_{uqt}$ is the return ratio of the recoverable products from the first customers markets when uncertain event *uqt* occurs. *uqt* is a discrete event related to the uncertain quantity of the return flow. Constraint (10) states that the flow of products between recovery centers ($i\epsilon I_{rc}$) and recycle centers ($i\epsilon I_{rcc}$) at time period *t* is equal to the flow of product handled by the recovery centers multiplied by the recycling ratio. $RRe_{duql}$ is the recycling ratio that depends on the product design *d* and the uncertain event *uql*. *uql* is a discrete event related to the uncertain quality of the return flow. In constraint (10), $I_{rdc}$ and $I_{fd}$ are re-distribution centers and final disposal places, respectively. It is important to note that three restrictions, similar to constraint (10), are established to ensure the flow of products between a) recovery centers and landfills, b) recovery and redistribution centers as well as recovery centers and factories. The flows depend on the disposing ratio ($Rdi_{duql}$), remanufacturing ratio ($Rm_{duql}$) and repairing ratio ($Rcc_{duql}$).

## Example

The real medium-size case study of a CLSC introduced by Kalaitzidou et al. (2015) was modified in order to illustrate the application of the two-stage multi-product model. Problem modifications include possible states of the uncertain parameters, cost associated with different product designs and revenues obtained by selling new, remanufactured and recycled products. The CLSC super-structure is composed of 5 suppliers (*s1* to *s5*), 15 factories (*f1* to *f15*), 15 distribution centers (*dc1* and *dc15*), 18 first market location (*fm1* to *fm18*), 5 second market locations (*sm1* to *sm5*), 15 recovery centers (*rc1* and *rc15*), 15 redistribution centers (*rdc1* and *rdc15*), 3 recycle centers (*rcc1* and *rcc3*) and 3 final disposal sites (*fd1* to *fd3*). The profit of the firm is optimized considering the alternative product and network designs. Ten final products are to be manufactured (*p1* to *p10*) using four raw materials (rm1 to rm4). Three years of four trimesters each one are considered as planning horizon. Transportation $CO_2$ emissions costs for moving raw materials and final products are also considered. Three possible levels for the uncertainty of quality and quantity of return flows are taken into account (low, medium and high quality: *uql1, uql2 and uql3*; high, medium and low quantity: *uqt1, uqt2 and uqt3*). Three alternative product designs are considered (*d1*, *d2* and *d3*). While *d1* and *d3* are associated to the design for recycling (DfRc) and the design for remanufacturing (DfRm), respectively; *d2* is an alternative design that adopts a philosophy of design that is between *d1* and *d3*.

## Computational Results

The formulation was coded in the optimizer software called GAMS (release 23.6.3), to show the relevance of the proposed two-stage approach. All computations were run with CPLEX 12.2, on a HP Z800 workstation with Intel Xeon x5650 2.66 GHz and 32 GB RAM memory for a 0.01 gap tolerance.

Given that the computational effort for solving the approach based on a two-layered tree of 9 scenarios with 28 nodes (1 root node and 3 nodes by each scenario) is huge, a scenario reduction algorithm is applied. In this work, a mix of fast backward and forward algorithms (available in the library SCENRED of GAMS) is used. In this case, the mathematical formulation obtained after the algorithm application maintains 70% of the original information of the problem. Thus, the two-layered tree obtained after applying the reduction algorithm is composed of 3 scenarios with 10 nodes.

The parameters associated with the risk measure adopt the following values: $\alpha p$= 0.5 and $\lambda$=1.5. Thus, they represent an intermediate level of confidence with a given increment in the importance of the risk with respect to the term connected with the expected values.

Table 1 shows the different cases solved. Cases 0 and 1 consider the problem as determinist, and Cases 2 to 6 take into account the uncertain conditions of the problem. In addition, while Cases 2 and 3 regard as objective function the expected profit (EP: *ER- EOC- SCSC*), Cases 4 to 6 consider the CVaRp as performance measure. In addition, it is important to note that while Case 6 solves simultaneously network and product design problems, Cases 4 and 5 only take into account one problem at a time. The results obtained for Cases 0 to 6 are shown in Tables 2, 3 and 4.

*Table 1. Cases characteristics*

| Case | OF | Network Structure | Considered Design | Quality Events | Quantity Events |
|---|---|---|---|---|---|
| **0** | **Profit** | -- | **d3** | **uql2** | **uqt2** |
| **1** | **Profit** | -- | **d1-d3** | **uql2** | **uqt2** |
| **2** | **EP** | -- | **d3** | **uql1-uql3** | **uqt1-uqt3** |
| **3** | **EP** | -- | **d1-d3** | **uql1-uql3** | **uqt1-uqt3** |
| **4** | **CVaRp** | -- | **d3** | **uql1-uql3** | **uqt1-uqt3** |
| **5** | **CVaRp** | **Fx** | **d1-d3** | **uql1-uql3** | **uqt1-uqt3** |
| **6** | **CVaRp** | -- | **d1-d3** | **uql1-uql3** | **uqt1-uqt3** |

- EP: Expected Profit= *ER- EOC- SCSC*
- --: Network Structure determined for the approach
- Fx: Network Structure obtained in Case 0

From the analysis of Table 2 it can be concluded that the product design affects the structure and performance of the network. The product design selected for Cases 1, 3 and 6 is different of the one pre-defined in Cases 0, 2 and 4 (*d3*). In addition, the product design is different depending on the objective function considered: EP or CVaRp. While *d2* is selected when using EP (Case 3), *d1* is chosen considering CVaRp (Case 6). On the other hand, the network structure for Cases 1 and 3 is different of the one obtained in Case 6. In all cases where the model selects the product design (Cases 1, 3, 5 and 6), profit improves. However, Case 6 has the lowest expected profit of Cases 1, 3, 5 and 6.

By comparing the objective function values for Cases 4, 5 and 6 (4124482, 4613788 and 4744306, respectively), it can be observed the benefits of simultaneous consideration of network design along with product design in Case 6. The solution of Case 6 presents the best value of the objective function CVaRp, which is interpreted as the solution with best feature to avoid the risk associated with declining profits.

Tables 3 and 4 show the comparison of Cases 1 to 6 with the reference case (Case 0). Cases 2 to 6 lead to solutions with a strong increase of the inventory cost and Cases 5 and 6 present the biggest decrease for transport cost, handling cost and production cost. Cases 5 and 6 also exhibit the biggest increase of return revenue and the biggest decrease of sales revenue (see Table 4).

In comparison with Case 0, Case 6 presents a greater expected profit (0.83%). In term of the expected profit, the differences between Cases 0 and 6 are small, nevertheless, the selection of a suitable product design and the explicit consideration of the uncertain quality and quantity of the return flows represents a significant improvement. Thus, the solution gets a reliable CLSC that explores the economic opportunities associated with the return flow.

*Table 2. Results for Cases 0 to 6*

| Case | Design | Facility Cost [$] | Reverse Cost [$] | Total Revenue [$] | Profit or Expected Profit [$] |
|---|---|---|---|---|---|
| **0** | **d3** | **2559600** | **258841** | **20492345** | **3057999** |
| **1** | **d2*** | **2613600** | **268346** | **20173447** | **3199489** |
| **2** | **d3** | **2559600** | **246724** | **20394835** | **2998160** |
| **3** | **d2*** | **2613600** | **255822** | **20092179** | **3141236** |
| **4** | **d3** | **2379600** | **246724** | **20384442** | **2968525** |
| **5** | **d1*** | **2646000** | **256764** | **19799434** | **3103231** |
| **6** | **d1*** | **2466000** | **256764** | **19799434** | **3083438** |

- All values are expressed in currency units [c.u.].
- * design determined by the model
- Reverse Cost: cost connected with the activities of recovery, remanufacturing, repairing, disposing and recycling

*Table 3. Relationship between Case 0 (reference case) and Cases 1 to 6 for costs*

| Cases | Transport Cost | Handling Cost | Purchasing Cost | Production Cost | Inventory Cost | Emissions Cost |
|---|---|---|---|---|---|---|
| **0-1** | **-1,8** | **-20,0** | **-11,0** | **-0,8** | **0,1** | **0,7** |
| **0-2** | **-0,3** | **-5,0** | **0,3** | **0,2** | **66,2** | **-1,3** |
| **0-3** | **-2,0** | **-24,0** | **-10,9** | **-0,8** | **65,7** | **-0,7** |
| **0-4** | **-0,3** | **-5,0** | **0,3** | **0,2** | **66,2** | **-1,2** |
| **0-5, 0-6** | **-4,3** | **-43,0** | **-7,9** | **-3,7** | **64,9** | **-0,4** |

Having Cases 4 and 5 the same objective function being different on the use of a predefined product design (case 4) or choosing the best, it can be seen Case 5 exhibits a larger network structure (see below) with a higher expected profit. The profit improvement is principally due to the decrease of transport (-4,1%), handling (-40%), purchasing (-8,2%) production (-3,9%) and the increase of return revenue (122%). Comparing Cases 3 and Case 5 where both choose the product design but have different objective functions it can be seen that Case 5 exhibits a smaller expected profit (-1,8%). The profit deterioration is principally due to the increase of purchasing (3,3%) and emissions (0,3%) costs as well as the decrease of sales revenue (-1.8%).

In terms of supply chain network, Figure 2 shows the network structure obtained for Case 5. Compared with Case 3, the structure differs in the distribution centers used. Thus, while Case 3 does not include a distribution center in France and it incorporates one in Switzerland, Case 5 adds a distribution center in France and it does not include one in Switzerland. In addition, in the Case 5 the installation costs of recovery and recycle centers are more expensive than in the Case 3 due to the selection of a product design for recycling (*d1*).

*Table 4. Relationship between Case 0 and Cases 1 to 6 for revenues*

| Cases | Return Revenue | Sales Revenue |
|---|---|---|
| **0-1** | **48,3** | **-1,8** |
| **0-2** | **-5,0** | **-0,5** |
| **0-3** | **40,9** | **-2,2** |
| **0-4** | **-3,5** | **-0,5** |
| **0-5, 0-6** | **114,2** | **-3,9** |

*Figure 2. CLSC structure for Case 5*

Considering the computational statistics, it is important to note that the solution for Case 6 was reached in approximately 15 hr of CPU time and the model has 52351 constraints, 317794 continuous variables and 96 discrete variables.

## Conclusions

This paper introduces a two-stage stochastic model that handles alternative options on product and network design in a CLSC context. The developed formulation is capable of selecting the appropriate entities and material flow considering a given product design, while the profit risk is addressed. Thus, the present work is a first attempt to fill a gap in the handling of risk along with the product and network design.

The novel features of the framework are the join consideration of the product design and the network design taking into account the minimization of the profit risk associated with uncertain quantity and quality of return flow. Thus, the risk management's objective is to assure uncertainty does not turn aside the behavior of the supply chain from the business goals.

From this work it can be concluded that the product design and the network design are highly connected. Thus, the characteristics of the network entities (for example, storage and processing capacities) depend on the product design selected.


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