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Integrating decisions of product and closed-loop supply chain design under uncertain return flows

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ABSTRACT

The shortage of natural resources, the need to take into account societal considerations, the emergence of new government regulations and the necessity to maintain and/or improve the economic benefit of the supply chain, have created a growing awareness on academia as well as industries towards the development of closed-loop supply chains (CLSCs), where explicitly products' life-cycles are accounted for. Concentrating on the problems of the product and network design for a multi-product, multi-echelon and multi-period CLSC, in this work a two-stage stochastic mixed integer linear model incorporating uncertainty on the quality and quantity of the return flows is proposed. In addition, risk management related to critical uncertain parameters is performed, where a conditional value at risk (CVaR) concept is applied to supply chain profits. The formulation considers decisions associated with the network design and, simultaneously, with the products to manufacture (new and remanufactured) and their associated raw materials (new and recovered). A network superstructure is considered accounting for 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. Optimal solutions with high economic and environmental benefits are obtained where the advantages of using the proposed approach are shown. A case study from a European consumer goods company is explored.

1. Introduction

The interest in the management of supply chains where the typical forward flow of materials from suppliers to end customers is extended to consider the flows of products returned by consumers (CLSCs) has markedly increased in the last years (Govindan and Soleimani, 2017). The shortage of natural resources, government regulations, consumer preferences, corporate environmental objectives and economic opportunities have been some of the drivers of the observed increased interest in considering the full life cycle of products. Thus, in general, firms that manufacture products require to consider the environmental impacts that they generate, which come from several activities: extracting and processing raw materials, manufacturing, assembly, distribution, packaging, use and maintenance of products. In addition, several activities developed at the end of life of the products must also be considered when the products environmental impact is accounted for. It should be noted that a friendly product from an environmental point of view is one that besides taking care of the impact due to the manufacture, transportation and use, also considers any consequence that may generate after use. Thus an environmentally friendly product should be designed to become a useful input for other products rather than only be transformed into waste after its useful life. Such concern has been translated into recent regulations, which not only limit or prohibit pollution and generation of waste in manufacturing processes, but also foster the incorporation of end-of-life products into new manufactured products, which are later on discarded by customers. These governmental policies correspond to the last tendency in order to try to decrease the environmental impact of the products controlling their substances/material content (see for example WEEE European regulation, Directive 2002/96/EC, 2003).

The environmental impact generated by a product can be reduced through different ways. Many authors (Handfield et al., 2001; Fiksel, 1996; Bras, 1997 and Ashley, 1993) emphasize that the greatest opportunity arises at the stage of product design if at the design stage the end-of-life of the products and associated environmental issues are considered. Thus, design strategies should be oriented to decrease undesirable materials, promote the use of low impact materials, increase the use of renewable

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materials and/or recovered materials, reduce the land use, promote the cleaner production, reuse and disassembly of components (Bras, 2007). In addition to all the environmental benefits of the mentioned design strategies, most of them also involve potential financial benefits, for example, recovering raw materials or extending product life cycles to sell remanufactured products may lead to an extended profit margin. Given the importance of the product designs and the product life cycles, it is extremely important to integrate decisions related to the materials, characteristics and performance of the products demanded by consumers along with strategic, tactical and operational decisions of CLSCs. Thus, questions about the structure of the forward and reverse networks, how and when discarded units must be sorted and processed, as well as what type of processes must be carried out should be taken into account simultaneously with product design alternatives. Therefore, the consideration of those decisions has a significant role in helping manufacturing firms to exploit economic opportunities connected with the products discarded by customers while environmental requirements are considered.

On the other hand, the key role of uncertain parameters in supply chain and operations management has been widely recognized as relevant (Cardoso et al., 2013; Govidan et al, 2015). Customers' demands, supply levels, return flows (quantity and quality of returned products) are critical factors with quite uncertain values in the supply chain context (Zeballos et al, 2012). In addition, the relationship between product design, CLSC design and management is strongly affected by the business environment changes. Product and network design in a CLSC are strategic decisions that should be determined considering the possible future circumstances of the business environment due to, for example, opening network entities with certain capabilities and capacities have a lasting and expensive impact in the network costs. Therefore, based on the aforementioned discussion, it is important to note that the need of dealing with uncertainty is unavoidable for SCM (Supply Chain Management), (McLean and Li, 2013; Barbosa-Póvoa, 2014; Govindan et al, 2015).

Given the previous mentioned issues, this paper presents a multi-product, multi-echelon and multi-period CLSC Model in which product and network design problems taking into account uncertain quality and quantity of the return flows are considered. The proposed approach for the Product and Network Design considering Uncertain Conditions (PNDUC) attempts to determine a suitable network structure considering the selection of a particular product design between several alternative designs. The network super-structure considered in the formulation is general and includes two types of customers (first and second markets). In order to create robust formulation's decisions, a two-stage stochastic mixed integer linear model is applied to address uncertain on the quality and quantity of the return flows. In addition, risk management related to the critical uncertain parameters is performed using a conditional value at risk (CVaR) concept applied to profits. Optimal solutions with high economic and environmental benefits while managing raw materials, products, return flows and network structure are obtained. To the best of our knowledge, there is no previous research that proposes a two-stage stochastic approach considering simultaneously the CLSC configuration and the product development considering a risk averse measure.

The remaining structure of this work is organized as follows. Section 2 presents an analysis of the state-of-the-art focused on the problems of CLSC configuration and product design. Furthermore, existing works addressing uncertainty and risk in supply chain management are also analyzed in the literature review. The model assumptions are stated in Section 3. A two-stage stochastic mixed-integer linear programming (MILP) formulation, able to represent the product design and the network configuration, is proposed in Section 4, the so called PNDUC. In Section 5, to highlight the benefits of the approach presented, a real medium-size case study of a CLSC is presented. In Section 6, computational results are presented and analyzed in order to show the advantages of using the PNDUC. Finally, conclusions are given in Section 7.

2. Literature survey

In this section, the existing literature dedicated to the present work topic is briefly described. For further details comprehensive reviews on CLSC can be found in Akcalı and Cetinkaya (2011), Souza (2013) and Govindan et al. (2015).

The advantages of the integration of forward and reverse logistics network have been extensively recognized by many researchers due to the strong influence on performance of the reverse network over the forward network and vice-versa. In addition, as pointed out in the previous section, a critical and necessary issue in supply chain and operations management is the consideration of volatile conditions in which the organizations operate. Thus, the necessity of formulations that handle different uncertain conditions in CLSCs is unavoidable. Some of the most recent and relevant papers associated to the design of CLSCs with uncertain parameters are as follows. Salema et al. (2007) proposed a linear mathematical model for a generic reverse logistics network where capacity limits, multi-product management and uncertainty on product demands and returns were accounted for. Uncertainty was considered while minimizing the expected cost. Francas and Minner (2009) introduced a two-stage stochastic formulation with the objective of analyzing optimal capacity acquisition and maximizing the expected profit in a CLSC under uncertain demand and returns. The formulation was tested with two different fixed network structures and two different market structures when new and remanufactures returned products are flowing through the network. Pishvaee et al. (2009) proposed a scenario-based stochastic framework considering customers demand, quantity and quality of returns as well as the variable costs as uncertain parameters. The network structure includes production/recovery, distribution–collection centers, customers, and disposal centers. The formulation objective function is to minimize the expected costs. Lee and Dong (2009) established a two-stage stochastic formulation for the design of a multi-period network with uncertain demand of forward products and supply of returned products at customers. The formulation performance measure is the minimization of the sum of current investment costs of building facilities as well as expected future processing and transportation costs. In addition, a heuristic algorithm based on simulated annealing was proposed in order to solve industrial examples. Pishvaee et al. (2011) proposed a framework based on the theory of Ben-Tal and Nemirovski (1999) for obtaining robust solutions to uncertain linear programs. The model was developed for minimizing the total costs of a single-product, single-period network accounting for production/recovery centers, hybrid distribution/collection centers, consumers, and disposal centers. The uncertain parameters considered for the authors are demand, quantity of return flows as well as transportation costs. Zeballos et al. (2012) introduced a two-stage scenario-based formulation to address the network design decisions in multi-period, multi-product CLSCs subject to uncertain conditions in the quantity and quality of return flows. The approach performance measure is the expected profits maximization. The network structure considered is composed of suppliers, factories, warehouses, customers and sorting centers. Amin and Zhang (2013) presented a stochastic framework based on scenarios for a single-period multi-product CLSC location problem considering demand and return as uncertain parameters, and including environmental factors on the objective function. The model seeks to minimize the expected costs of a network with a superstructure composed of multiple plants, collection centers and several consumers. Cardoso et al. (2013) introduced a mathematical formulation for a generic network structure with customers demand as uncertain parameter. The model performance measure is to maximize the expected net present value considering the entity capacity expansion and dynamic transportation links. Zeballos et al. (2014) proposed a multi-stage stochastic framework for addressing the design and planning of a general closed-loop network structure composed of 10 layers with uncertain levels in customers' demands and raw material supplies. The objective function aims to minimize the expected cost minus the expected revenues due to the return flows from repairing and decomposition centers to the forward network. Khatami et al. (2015) presented a two-stage mathematical approach for designing a multi-period multi-commodity CLSC under demand and return uncertainties. The framework was developed for a network redesign determining the initial capacity of new facilities and the amount of capacity expansion for existing ones. The approach seeks to minimize the investment costs and the expected value of the operational costs. In addition, to solve a real-life case, Khatami et al. (2015) applied a Benders' decomposition method. Dutta et al. (2016) presented a recovery framework that employs buy-back offer at retailer level with an optimization formulation for a multi-period CLSC under demand and capacity uncertainty. The integrated approach determines optimal buy-back price that needs to be offered to consumers along with the decisions of manufacturing, remanufacturing and recycling quantity for products, components and raw materials. The uncertainty issues are addressed with chance constrained programming. The objective of the approach is to minimize the total cost of the CLSC in presence of a three way recovery and buy-back offer. Jeihoonian et al. (2017) introduced a two-stage stochastic mixed-integer programming formulation for the closed-loop network design problem in the context of modular structured products with several types of recovery options. The quality of the return flow is considered as uncertain parameter. The objective function is to maximize the expected profit for all realized quality state scenarios. To solve the problem addressed, the authors used a scenario reduction scheme preserving the most pertinent scenarios and, then, applied a L-shaped algorithm enhanced with surrogate constraints and Pareto-optimal cuts.

As it can be seen, there are various papers in literature that addressed the CLSC design problem considering uncertain conditions. Nevertheless, the above papers consider as objective function only expected values of magnitudes such as cost, revenues and profit and the risk associated with the variability of random events is ignored. These approaches are called risk-neutral. In addition, only few works have captured uncertainty in the quality of the return flow (Zeballos et al., 2012, Chen et al., 2015 and Jeihoonian et al., 2017). At present time, few papers have introduced risk averse considerations. Some of the most recent and relevant works that explicitly address the variability of uncertain parameters in CLSC are: Ramezani et al. (2013), Soleimani et al.(2014), Subulan et al. (2015) and Zeballos et al. (2016). Ramezani et al. (2013) presented a robust approach for the design problem of a multi-product, multi-echelon CLSC in which the demand and the return rate are uncertain. Based on the profit, the objective of the formulation is to find a robust solution that minimizes the maximum difference between the optimal objective function value and the resulting objective function for all possible scenarios. The authors proposed a scenario relaxation algorithm to obtain robust solutions with acceptable CPU time. Soleimani et al. (2014) presented a two-stage stochastic approach to deal with the location-allocation of entities in a CLSC under uncertain demand and prices of new and returned products. The authors used risk measures such as mean absolute deviation (MAD), value at risk (VaR) and conditional value at risk (CVaR), when the total profits are considered as objective function. It is important to note that risk measures are applied only to costs, and revenues are considered in the performance measure as expected values. Subulan et al. (2015) proposed a scenario based stochastic and possibilistic framework for a design problem with financial and collection risks. The approach includes different risk measures such as variability index, downside risk and CVaR in order to take into account the total cost and the total collection coverage as general objective function. Zeballos et al. (2016) proposed a comprehensive risk averse multi-stage model for dealing with the design and planning problem of a CLSC considering adjustments in the supply chain structure during the planning horizon as well as uncertainty in supply and customer demands. The performance of the CLSC is evaluated considering profit maximization. This work includes five objective functions associated to different risk adversity criteria: two based on the mean absolute deviation and three ones centered on the conditional value at risk (CVaR) concept.

According to Souza (2013), the interface between new product design and recovery activities is still an open area of research. The author remarks that recycling has been incorporated in research dealing with take-back legislation, however, the comprehensive design of product and respective CLSC with a clear focus on recycling is a very new research area. Despite the importance of coordinating product design with reverse network structures and activities, few papers consider the full problem. It is important to note that present models addressing the product design problem are focused on determining the number of new and remanufactured products to be offered, product attribute settings of the new and remanufactured products, sale prices and product return rates, without considering decisions connected with the network structure (for example, Kwak and Kim, 2015; Aydin et al., 2016). Some of the early papers addressing product design and location-allocation of entities in CLSCs are focused on the incorporation of supplier activities as part of the network and no the total CLSC (Krikke et al., 2003; Fixson 2004). More recently Metta and Badurdeen (2013) proposed a framework with the objective of evaluating SC configurations along with product designs. However, the approach addresses the problem by parts (hierarchical formulation) and does not take into account the existence of uncertain conditions.

The overview of the existing literature implies that product design, location-allocation of entities in a CLSC under uncertain parameters and risk management are four of the most important issues in supply chains that have not however been considered simultaneously. In this paper, a framework to determine the network design for a multi-product, multi-echelon and multi-period CLSC considering uncertain quality and quantity of the return flows is proposed. In addition, product design is also determined while the risk management related to critical uncertain parameters is performed.

3. Problem description

The product and network design problems 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 are addressed in this work. Fig. 1 represents the different types of entities considered as part of the CLSC. Moreover, it shows a schematic representation of raw materials (*rm*) and final products (*p*) flows in the CLSC structure.

The basic settings considered for the CLSC in study are:

- The planning horizon is divided into several time periods.
- Capacities and locations of the entities that can be included on the CLSC are known in advance.
- New and remanufactured products are differentiated for customers.

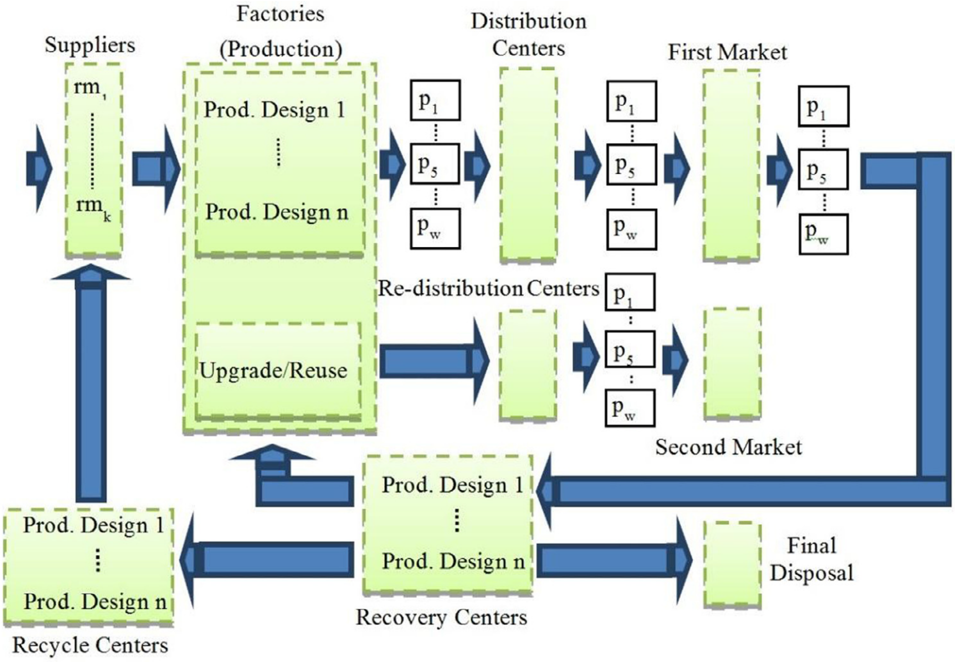

Fig. 1. CLSC structure and Schematic representation of product flows.

- The amount of space between entities and transportation capacities are known and fixed.
- The unit costs of purchasing, inventory, transportation and CO_2 emissions are known in advance.
- Not all products sold are recovered after their useful life.
- The quantity of returned products is considered as a fraction of the final products delivered to customers (Salema et al., 2010).
- Material flow connections between entities of the same type are allowed.
- Maximum and minimum capacities for inventory, production and transportation are considered.
- Demands are related to 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.
- The raw materials requirements depend on the design.
- Each product design leads to different handling and processing of the products after they are discarded by customers.

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. Several product designs are considered and each product design has dissimilar characteristics, which are mainly associated with the processing route of the final products after being discarded by customers. Two designs strategies are modeled: the design for recycling (DfRc) and for remanufacturing (DfRm). DfRc and DfRm are considered as opposed designs. While DfRc focuses on facilitating the recycling of raw materials during the entire product life-cycle, DfRm pays attention to recover, check, and utilize modules, parts, components of final products discarded by customers (Bras, 2010). In addition, other alternative designs are considered leading to different levels of remanufacturing and recycling of products. Thus, the alternative designs are associated with distinct philosophies of design that are between the principles of DfRm and DfRc involving a combination of strategies to reduce to minimal the use of undesirable materials, to promote the use of low impact materials, to increase the use of renewable materials and/or recovered materials, to reduce the land use, to promote the cleaner production, to reuse and disassembly of components.

The following assumptions associated with the product designs are considered:

- DfRm is associated with tasks performed predominantly by trained employees (Bras, 2007).
- DfRc is connected to activities based on automatic equipment involving mechanical and/or chemical recovery of raw materials (Bras, 2007).
- 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 revenues (Ilgın and Gupta, 2012). In addition, Ferguson and Souza (2010), point out that in many cases the remanufacturing processes are less expensive than producing a brand new unit of the product (at least on the margin) because many parts and components can be reused, thus avoiding the need to procure them from suppliers.
- 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).

Given the mentioned assumptions, in this work the product designs directly influence the network fixed costs as they affect mainly the capabilities and capacities of network entities, such as plants, 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, end-of-life products flow through the reverse network at different rates, depending on their origin and destination. Fig. 1 shows the entities affected by the alternative product designs.

4. PNDUC problem formulation

The PNDUC approach is a stochastic MILP approach that addresses the product design and CLSC configuration under uncertain conditions related to the quality and quantity of return flows. The product design involves the selection of one product design between all feasible alternatives in a CLSC context. Thus, the set of final products to be delivered to customers are produced according to a unique product design. The optimization problem consists of a profit maximization objective function and constraints model conditions associated with CLSC structure, transportation, material supply, final products flows, production, resources, products demand and inventory capacity.

The uncertain conditions of the problem and the risk management are addressed using a two-stage stochastic approach. The CVaR concept is incorporated in the model as a performance measure in order to manage variability and risk associated with the profit. In the proposed approach, a finite number of scenarios, with certain probability, represent the quality and quantity of the return flows. The formulation uses a two-layered scenario tree to denote the uncertain conditions. Each tree node is associated with a certain realization of the two uncertain parameters. In this work, the random parameters are considered as independent events. Since the approach involves two layers, the levels of quality and quantity of return flows adopted after the first planning period depend on the events occurrence in the first planning period. Thus, after the events occurrence 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.

Variables modeling the selection of a given product design for the network and entities setting variables are considered as first-stage variables since these do not depend on the scenarios circumstances and must adopt values before the realization of the uncertain parameters. The second-stage variables are those related to production, handling, distribution and storage variables since these must be determined in the face of uncertainty. As the selected product design affects the production cost and the rate of production of several entities, it is important to remark that the selection of the most suitable entities for recovery, redistributions, recycle and final disposal centers depends on the product design. Supply chain 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 constraints are related to: the selection of a given product design; opening of network entities; minimum and maximum limits for the raw material supply; customer demand of first market; minimum value of the second market demand; material balances at each entity; minimum and maximum transportation capacity between two entities; minimum storage level in the network entities; maximum bounds for the use of manufacturing resources; maximum and minimum processing capacity in factories; existence of incoming and outgoing transport movements.

The processing and storage of the reverse network entities depend on the product design. Also, 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. These issues are taken into account in the respective constraints. The definition of sets, variables and parameters of the model are shown in Appendix A.

4.1. Objective function

A utility function that can be used in the stochastic model is to maximize the profit. This goal considers the expected revenues (*ER*), the expected operational costs (*EOC*), the supply chain structure costs (*SCSC*) as well as a term that quantify the risk (*RM*) (see Eq. (1)). The latter is affected by a non-negative weighted factor (β), which corresponds to a trade-off coefficient to model the relative importance of the risk term with respect to the expected values of revenues and costs.

$$Maximize\ Utility\ Function = ER - EOC - SCSC - \beta * RM \tag{1}$$

The revenues of scenario s (R_s) are achieved by considering the selling of new and recycled products and by taking into account the recovered materials into the forward network (see Eq. (2)). Each scenario s consists of a particular sequence of events Ω_{nt} from the root node until a given leaf node at the last time period. Ω_{nt} represents the events $uql{\in}Eql$ and $uqt{\in}Eqt$ that occur for node n at time period t. R_s is determined for each scenario s considering periods $t1$ to tf, and all products transported between each couple of the following entities: distribution centers - first market, redistribution centers - second market, recovery centers - plants, recycling centers - suppliers.

Considering all the individual contributions of the scenarios, the expected revenues (*ER*) of the problem is computed (see Eq. (3)). *ER* is obtained adding the product of R_s with the occurrence probability of scenario s (Pb_s), that is computed multiplying the individual probabilities of the events that compose the scenario s (Pb_s= $\{(P_{uql}P_{uqt})_{\Omega nt1}\ (P_{uql}P_{uqt})_{\Omega nt2}\ (P_{uql}P_{uqt})_{\Omega nt3}\ \ldots(P_{uql}P_{uqt})_{\Omega nT}\}$).

$$\begin{aligned}
\mathrm{R_s}: \sum_{teT}\ \sum_{n\in\{NS_S\cap NT_t\}} \Bigg(& \sum_{i\in I_{dc}}\ \sum_{j\in I_{fm}}\ \sum_{p\in P^{fp}} rsfm_{ip}q_{ijptn} \\
& + \sum_{\in I_{rdc}}\ \sum_{j\in I_{sm}}\ \sum_{p\in P^{fp}} rssm_{ip}q_{ijptn} \\
& + \sum_{i\in I_{rc}}\ \sum_{j\in I_f}\ \sum_{p\in P^{fp}} rrp_{ip}q_{ijptn} + \sum_{i\in I_{rcc}}\ \sum_{j\in I_s}\ \sum_{p\in P^{rm}} rrs_{ip}q_{ijptn} \Bigg)
\end{aligned} \tag{2}$$

$$\mathrm{ER}: \quad \sum_{s\in SC} Pb_s\ R_s \tag{3}$$

The operational costs of scenario s (OC_s) are obtained by adding the costs considering periods $t1$ to tf. In Eq. (4), OC_s is computed adding the costs associated with: the handling of products entering/leaving entities such as plants, distribution, recovery and re-distribution centers; production; transport; storage; the recovery and elimination processes of the returned products; recycling process; purchasing of raw material and CO_2 emissions. It is important to note that the transportation CO_2 emissions costs are calculated by multiplying the emission costs by the rate of flow of material transferred from a given entity to another entity. Finally, the expected operational costs (*EOC*) are calculated in Eq. (5). The deterministic version of the operational costs can be found in Kalaitzidou et al. (2015).

$$\begin{aligned}
\mathrm{OC_s}: \sum_{t\in T}\ \sum_{n\in\{NS_S\cap NT_t\}} \Bigg[& \sum_{i\in I_f} \Bigg(\sum_{p\in P^{rm}} C_{pi}^{DH} \Bigg(\sum_{j\in I_s} q_{jiptn} + \sum_{j\in I_{rc}}\ \sum_{n'\in Na_n} q_{jipt-1n'} \Bigg) \\
& + \sum_{p\in P^{fp}} C_{pi}^{DH} \sum_{j\in I_{dc}} q_{ijptn} \Bigg) + \sum_{i\in I_{dc}}\ \sum_{p\in P^{fp}} C_{pi}^{DH} \Bigg(\sum_{j\in I_{fm}} q_{ijptn} + \sum_{j\in I_f} q_{jiptn} \Bigg) \\
& + \sum_{i\in I_{dc}}\ \sum_{p\in P^{fp}} C_{pi}^{DH} + \Bigg(\sum_{j\in I_{fm}} q_{jiptn} + \sum_{j\in I_{fd}} q_{ijptn} + \sum_{j\in I_{rdc}} q_{ijptn} \\
& + \sum_{j\in I_f} q_{ijptn} + \sum_{j\in I_{rcc}} q_{ijptn} \Bigg) + \sum_{i\in I_f}\ \sum_{r\in R} \delta_{ri}^{P} \sum_{p\in P^{rm}}\ \sum_{d\in D} \lambda_{ipr} p_{diptn}
\end{aligned}$$

$$+\sum_{i,j\epsilon A}\sum_{p\epsilon P}C^{T}_{pij}\ q_{ijptn}+\left(\sum_{i\epsilon I^{fi}}\sum_{p\epsilon P^{fp}}\sum_{n'\epsilon Na_n}C^{IP}_{pij}\frac{(i_{iptn}+i_{ipt-1n'})}{2}\right.$$
$$\left.+\sum_{i\epsilon I^{ri}}\sum_{p\epsilon P^{fp}}\sum_{n'\epsilon Na_n}C^{IDR}_{pij}\frac{(i_{iptn}+i_{ipt-1n'})}{2}\right)$$
$$+\left(\sum_{i\epsilon I_{fm}j\epsilon I_{rc}}\sum_{p\epsilon P^{fp}}\left(C^{RV}_{pi}q_{ijptn}+\ C^{RP}_{pi}RCC\ q_{ijptn}+C^{RM}_{pi}RM\ q_{ijptn}\right)\right.$$
$$\left.+\sum_{i\epsilon I_{rc}j\epsilon I_{fd}}\sum_{p\epsilon P^{fp}}C^{Di}_{pi}q_{ijptn}\right)$$
$$\left.+\left(\sum_{i,j\epsilon A^{f}}\sum_{p\epsilon P}ec^{f}q_{ijptn}+\sum_{i,j\epsilon A^{r}}\sum_{p\epsilon P}ec^{r}q_{ijptn}\right)\right] \quad (4)$$

$$\text{EOC}:\quad \sum_{s\epsilon SC}Pb_s\ OC_s \quad (5)$$

Supply Chain Structure Cost (SCSC) symbolizes the costs of opening facilities at the beginning of the planning horizon. Eq. (6) determines the cost of the network facilities considering the characteristics of the entities due to the requirements of the product design selected. Eq. (6) is composed of seven terms. While the first four terms only depend on whether the entities are used or not, the last three terms take into account if entities are incorporated to the network or not and the product design selected. The computation of the last three terms on Eq. (6) requires additional constraints. Constraints (7)–(9) compute the costs of establishing recovery and recycling centers, as well as factories considering a given product design. The costs depend on the product design due to the different resources required for each design. In addition, it is important to note that, in factories, the use of resources in function of the product designs is also taking into account through the rate of production of the products.

$$\text{SCSC}:\quad \sum_{i\epsilon I_{fd}}C^{Di}_{i}\ y_i+\sum_{i\epsilon I_{dc}}C^{D}_{i}\ y_i+\sum_{i\epsilon I_{rdc}}C^{DR}_{i}\ y_i+\sum_{i\epsilon I_s}C^{S}_{i}\ y_i$$
$$+\sum_{i\epsilon I_{rcc}}\upsilon C^{Re}_{i}+\sum_{i\epsilon I_p}\upsilon C^{P}_{i}+\sum_{i\epsilon I_{rc}}\upsilon C^{R}_{i} \quad (6)$$

$$\upsilon C^{Re}_{i}\geq C^{Re}_{id}\ y_i\ -\ M(1-yd_d)\quad \forall i\epsilon I_{rcc}\quad \forall d\epsilon D \quad (7)$$

$$\upsilon C^{P}_{i}\geq C^{P}_{id}\ y_i\ -\ M(1-yd_d)\quad \forall i\epsilon I_{p}\quad \forall d\epsilon D \quad (8)$$

$$\upsilon C^{R}_{i}\geq C^{R}_{id}\ y_i\ -\ M(1-yd_d)\quad \forall i\epsilon I_{rc}\quad \forall d\epsilon D \quad (9)$$

The CVaR concept is employed as Risk Measure (RM). Since in the proposed work it is assumed that the random conditions are represented by a finite number of scenarios with certain probabilities, the CVaR expression used is the one obtained by Noyan (2012) for the case of finite probability space. The application of the CVaR concept to the profit variability leads to two terms shown in (10): while SCSC is associated with the costs for opening facilities at the beginning of the planning horizon and that does not depend on the scenarios, CVaRp is connected with the values of revenues and costs for the different scenarios considered. The term CVaRp is the one that effectively allows reducing the likelihood that the network design with a certain product design incurs in large decreases in profit due to the uncertainty in the quality and quantity of the return flows. The steps for reaching the term (10) from a performance measure of the type Mean-CVaR was proved in Noyan (2012). While the term (11) is the effective risk measure, the term (12) is an auxiliary constraint of the term (11). Term (11) quantifies the risk that exists below a given value of profit, which is imposed by the confidence level (αp), while term (12) determines the difference between a given level of expected profit (ηp) and the profit of the scenarios that are outside of the confidence interval (1-αp). During the optimization process is computed ηp considering the selected confidence level. When the difference between the revenues of scenario s (R_s) minus the operational cost of the same scenario s (OC_s) is lower than ηp, the deviational variable $dv\eta p_s$ adopts a value greater than zero. From a conceptually point of view, it can be said that the variable $dv\eta p_s$ quantifies the reduction of profit of the scenario s when its profits are less than ηp. When considering large confidence intervals (small values of αp parameter) more scenarios are considered in constraint (12) and consequently the solution becomes more averse to incurring in large decreases in profit for certain scenarios.

$$\text{RM}:\quad CVaRp-SCSC \quad (10)$$

$$\text{CVaRp}:\quad \eta p-\frac{1}{(1-\alpha p)}\sum_{s\epsilon SC}[Pb_s(dv\eta p_s)]\quad \forall s\in SC \quad (11)$$

$$(R_s-OC_s)-\eta p+dv\eta p_s\geq 0\quad \forall s\in SC \quad (12)$$

The objective function (13) is obtained replacing the term (10) in Eq. (1). Thus, the performance measure includes four terms: the expected profit (ER-EOC), the costs for opening facilities at the beginning of the planning horizon (SCSC) (affected by the factor $(1+\beta)$ due to application of the CVaR concept to the profit variability) and the term CVaRp.

$$\text{OFCVaRp}:\quad ER-EOC-(1+\beta)\ SCSC+\beta\ CVaRp \quad (13)$$

In addition, in order to highlight the importance of the model (taking into account the joint consideration of the problems of product and network design, as well as the effects of uncertainty and risk) to address the environmental impact of the chain, two performance measures associated with the flow of recycled raw materials that return to the forward network through the suppliers and factories are considered.

The first objective function is to maximize the mean value of the revenues obtained by returning materials into the forward network (see Eqs. (14) and (15)). RSP_s is determined for each scenario s considering periods $t1$ to tf, and all products transported between recycling centers and suppliers, as well as recovery centers and factories. Considering all the individual contributions of the scenarios, the expected revenues obtained by returning materials to suppliers and factories (*OFERS*) are computed (see Eq. (15)). *OFERSP* is obtained adding the product of RSP_s with the occurrence probability of scenario s (Pb_s).

$$\text{RSP}_s:\quad \sum_{t\epsilon T}\sum_{n\epsilon\{NS_s\cap NT_t\}}\left(\sum_{i\epsilon I_{rc}}\sum_{j\epsilon I_f}\sum_{p\epsilon P^{fp}}rrp_{ip}q_{ijptn}\right.$$
$$\left.+\sum_{i\epsilon I_{rcc}}\sum_{j\epsilon I_s}\sum_{p\epsilon P^{rm}}rrs_{ip}q_{ijptn}\right) \quad (14)$$

$$\text{OFERSP}:\quad \sum_{s\epsilon SC}Pb_s\ RSP_s \quad (15)$$

The other objective function is obtained by applying the CVaR concept to the variability of the revenues obtained by returning materials into the forward network. Thus, CVaRrsp allows reducing the likelihood that the network design with a certain product design incurs in large decreases in revenues due to the uncertainty in the quality and quantity of the return flows. Term (16) quantifies the risk that exists under a certain value of revenues, which is imposed by the confidence level (αr), while constraint (17) determines the difference between a given level of expected revenues

(ηr) and the revenues of the scenarios that are outside of the confidence interval (1-αr). Thus, the constraint (17) is an auxiliary constraint of the term (16) that is effectively the risk measure. ηr is calculated during the optimization process taking into account the selected confidence level. When the difference between the revenues of scenario s (RSP_s) is lower than ηr, the deviational variable $dv\eta r_s$ adopts a value greater than zero. Conceptually, the variable $dv\eta r_s$ quantifies the reduction of revenues of the scenario s when its revenues are less than ηr. When considering large confidence intervals (small values of αr parameter) more scenarios are considered in term (17) and consequently the solution becomes more averse to incurring in large decreases in revenues for certain scenarios.

$$\text{CVaRrsp}: \quad \eta r - \frac{1}{(1-\alpha r)} \sum_{s \in SC} [Pb_s (dv\eta r_s)] \quad \forall s \in SC \tag{16}$$

$$RSP_s - \eta r + dv\eta r_s \geq 0 \quad \forall s \in SC \tag{17}$$

Finally, the performance measure includes two terms: the expected revenues and the term CVaRrsp affected by the weighted factor (β), which corresponds to a trade-off coefficient to model the relative importance of the risk term with respect to the expected values of revenues.

$$\text{OFCVaRrsp}: \quad \sum_{s \in SC} Pb_s \; RSP_s \; + \beta \; CVaRrsp \tag{18}$$

4.2. Constraints

It is important to note that since the main model variables, such as production rates (p_{diptn}), inventory (in_{iptn}), material flows ($q_{ii'ptn}$), depend on the time period and on the node of the scenario tree considered, most of the constraints included in this section are developed for a precise node n at certain time t that belong to a given scenario s.

$$\sum_{d \in D} yd_d = 1 \tag{19}$$

$$\sum_{d' \in D,\ d' \neq d} \sum_{i \in I_f} \sum_{p \in P^{fp}} \sum_{t \in T} \sum_{n \in \{NS_s \cap NT_t\}} p_{d'iptn} \leq M(1 - yd_d) \quad \forall\, d \in D \tag{20}$$

$$p_{diptn} \geq -M(1 - yd_d) + y_i P_{pid}^{min}$$
$$\forall\, d \in D, \quad \forall\, i \in I_f, \quad \forall\, p \in P^{fp}, \quad \forall t \in T, \quad \forall\, s \in SC, \quad \forall\, n \in \{NT_t \cap NS_s\} \tag{21}$$

$$p_{diptn} \leq M(1 - yd_d) + y_i P_{pid}^{max}$$
$$\forall\, d \in D, \quad \forall\, i \in I_f, \quad \forall\, p \in P^{fp}, \quad \forall t \in T, \quad \forall\, s \in SC, \quad \forall\, n \in \{NT_t \cap NS_s\} \tag{22}$$

$$in_{iptn} = \sum_{j \in I_f\, j \neq i} q_{jiptn} + \sum_{d \in D} p_{diptn} - \sum_{j \in I_{dc}} q_{ijptn} - \sum_{j \in I_f\, j \neq i} q_{ijptn}$$
$$\forall\, i \in I_f, \quad \forall\, p \in P^{fp}, \; t_1, \quad \forall\, s \in SC, \quad \forall\, n \in \{NT_t \cap NS_s\} \tag{23}$$

$$in_{iptn} = \sum_{n' \in Na_n} in_{ip(t-1)n'} + \sum_{j \in I_f\, j \neq i} q_{jiptn} + \sum_{j \in I_{rc}} \sum_{n' \in Na_n} q_{jip(t-1)n'} + \sum_{d \in D} p_{diptn} - \sum_{j \in I_{dc}} q_{ijptn} - \sum_{j \in I_f\, j \neq i} q_{ijptn}$$
$$\forall\, i \in I_f, \quad \forall\, p \in P^{fp}, \quad \forall t \in T \backslash \{t_1\}, \quad \forall\, s \in SC, \quad \forall\, n \in \{NT_t \cap NS_s\} \tag{24}$$

$$in_{iptn} = \sum_{j \in I_{dc}\, j \neq i} q_{jiptn} + \sum_{j \in I_f} q_{jiptn} - \sum_{j \in I_{fm}} q_{ijptn} - \sum_{j \in I_{dc}\, j \neq i} q_{ijptn}$$
$$\forall\, i \in I_{dc}, \quad \forall\, p \in P^{fp}, \; t_1, \quad \forall\, s \in SC, \quad \forall\, n \in \{NT_t \cap NS_s\} \tag{25}$$

$$in_{iptn} = \sum_{n' \in Na_n} in_{ip(t-1)n'} + \sum_{j \in I_{dc}\, j \neq i} q_{jiptn} + \sum_{j \in I_f} q_{jiptn} - \sum_{j \in I_{fm}} q_{ijptn} - \sum_{j \in I_{dc}\, j \neq i} q_{ijptn}$$
$$\forall\, i \in I_{dc}, \quad \forall\, p \in P^{fp}, \quad \forall t \in T \backslash \{t_1\}, \quad \forall\, s \in SC, \quad \forall\, n \in \{NT_t \cap NS_s\} \tag{26}$$

$$in_{iptn} = \sum_{j \in I_{fm}} q_{jiptn} + \sum_{j \in I_{rc}\, j \neq i} q_{jiptn} - \sum_{j \in I_{rdc}} q_{ijptn} - \sum_{j \in I_f} q_{ijptn} - \sum_{j \in I_{rcc}} q_{ijptn} - \sum_{j \in I_{fd}} q_{ijptn} - \sum_{j \in I_{rc}\, j \neq i} q_{ijptn}$$
$$\forall\, i \in I_{rc}, \quad \forall\, p \in P^{fp}, \; t_1, \quad \forall\, s \in SC, \quad \forall\, n \in \{NT_t \cap NS_s\} \tag{27}$$

$$in_{iptn} = \sum_{n' \in Na_n} in_{ip(t-1)n'} + \sum_{j \in I_{fm}} q_{jiptn} + \sum_{j \in I_{rc}\, j \neq i} q_{jiptn} - \sum_{j \in I_{rdc}} q_{ijptn} - \sum_{j \in I_f} q_{ijptn} - \sum_{j \in I_{rcc}} q_{ijptn} - \sum_{j \in I_{fd}} q_{ijptn} - \sum_{j \in I_{rc}\, j \neq i} q_{ijptn}$$
$$\forall\, i \in I_{rc}, \quad \forall\, p \in P^{fp}, \quad \forall t \in T \backslash \{t_1\}, \quad \forall\, s \in SC, \quad \forall\, n \in \{NT_t \cap NS_s\} \tag{28}$$

$$in_{iptn} = \sum_{j \in I_{rdc}\, j \neq i} q_{jiptn} + \sum_{j \in I_{rc}} q_{jiptn} - \sum_{j \in I_{sm}} q_{ijptn} - \sum_{j \in I_{rdc}\, j \neq i} q_{ijptn}$$
$$\forall\, i \in I_{rdc}, \quad \forall\, p \in P^{fp}, \; t_1, \quad \forall\, s \in SC, \quad \forall\, n \in \{NT_t \cap NS_s\} \tag{29}$$

$$in_{iptn} = \sum_{n' \in Na_n} i_{ip(t-1)n'} + \sum_{j \in I_{rdc}\, j \neq i} q_{jiptn} + \sum_{j \in I_{rc}} q_{jiptn} - \sum_{j \in I_{sm}} q_{ijptn} - \sum_{j \in I_{rdc}\, j \neq i} q_{ijptn}$$
$$\forall\, i \in I_{rdc}, \quad \forall\, p \in P^{fp}, \quad \forall t \in T \backslash \{t_1\}, \quad \forall\, s \in SC, \quad \forall\, n \in \{NT_t \cap NS_s\} \tag{30}$$

$$in_{iptn} \geq \frac{hp}{dcmf} \left(\sum_{j \in I_{dc}} q_{ijptn} + \sum_{j \in I_f\, j \neq i} q_{ijptn} \right)$$
$$\forall\, i \in I_f, \quad \forall\, p \in P^{fp}, \quad \forall t \in T, \quad \forall\, s \in SC, \quad \forall\, n \in \{NT_t \cap NS_s\} \tag{31}$$

$$in_{iptn} \geq \frac{hp}{dcmf} \left(\sum_{j \in I_{fm}} q_{ijptn} + \sum_{j \in I_{dc}\, j \neq i} q_{ijptn} \right)$$
$$\forall\, i \in I_{dc}, \quad \forall\, p \in P^{fp}, \quad \forall t \in T, \quad \forall\, s \in SC, \quad \forall\, n \in \{NT_t \cap NS_s\} \tag{32}$$

$$in_{iptn} \geq \frac{hrd}{dcmf} \left(\sum_{j \in I_{sm}} q_{ijptn} + \sum_{j \in I_{rdc}\, j \neq i} q_{ijptn} \right)$$
$$\forall\, i \in I_{rdc}, \quad \forall\, p \in P^{fp}, \quad \forall t \in T, \quad \forall\, s \in SC, \quad \forall\, n \in \{NT_t \cap NS_s\} \tag{33}$$

$$\sum_{j \in I_s} q_{jiptn} = \sum_{d \in D\, \forall} \sum_{p' \in P^{fp}} w_{dpp'} \; p_{dip'tn}$$
$$\forall\, i \in I_f, \quad \forall\, p \in P^{rm}, \quad \forall t \in T, \quad \forall\, s \in SC, \quad \forall\, n \in \{NT_t \cap NS_s\} \tag{34}$$

$$\sum_{d \in D\, \forall} \sum_{p \in P^{fp}} \lambda_{pir} \; p_{diptn} \leq E_{ri} \quad \forall\, i \in I_f, \quad \forall\, r \in R, \quad \forall t \in T, \quad \forall\, s \in SC,$$
$$\forall\, n \in \{NT_t \cap NS_s\} \tag{35}$$

$$\sum_{j\epsilon I_{rc}} q_{ijptn} = \sum_{j\epsilon I_{dc}} q_{jiptn} \sum_{uqt\epsilon Eqt_n} RC_{uqt}$$
$$\forall\ i\epsilon I_{fm},\quad \forall\ p\epsilon P^{rm},\quad \forall t\epsilon T,\quad \forall\ s\epsilon SC,\quad \forall\ n\ \epsilon\{NT_t\cap NS_s\} \qquad (36)$$

$$\sum_{j\epsilon I_{rcc}} q_{ijptn} \geq \left(\sum_{j\epsilon I_{rcc}} q_{ijptn} + \sum_{j\epsilon I_{rdc}} q_{ijptn} + \sum_{j\epsilon I_{fd}} q_{ijptn} + \sum_{j\epsilon I_f} q_{ijptn} - \sum_{j\epsilon I_{rc}\ j\neq i} q_{ijptn} \right) * \sum_{uql\epsilon Eql_n} RRe_{duql} - M(1-yd_d)$$
$$\forall\ d\epsilon D,\quad \forall\ i\epsilon I_{rc},\quad \forall\ p\epsilon P^{fp},\quad \forall t\epsilon T,\quad \forall\ s\epsilon SC,\quad \forall\ n\ \epsilon\{NT_t\cap NS_s\} \qquad (37)$$

$$\sum_{j\epsilon I_{fd}} q_{ijptn} \geq \left(\sum_{j\epsilon I_{rcc}} q_{ijptn} + \sum_{j\epsilon I_{rdc}} q_{ijptn} + \sum_{j\epsilon I_{fd}} q_{ijptn} + \sum_{j\epsilon I_f} q_{ijptn} - \sum_{j\epsilon I_{rc}\ j\neq i} q_{ijptn} \right) * \sum_{uql\epsilon Eql_n} Rdi_{duql} - M(1-yd_d)$$
$$\forall\ d\epsilon D,\quad \forall\ i\epsilon I_{rc},\quad \forall\ p\epsilon P^{fp},\quad \forall t\epsilon T,\quad \forall\ s\epsilon SC,\quad \forall\ n\ \epsilon\{NT_t\cap NS_s\} \qquad (38)$$

$$\sum_{j\epsilon I_{rdc}} q_{ijptn} \geq \left(\sum_{j\epsilon I_{rcc}} q_{ijptn} + \sum_{j\epsilon I_{rdc}} q_{ijptn} + \sum_{j\epsilon I_{fd}} q_{ijptn} + \sum_{j\epsilon I_f} q_{ijptn} - \sum_{j\epsilon I_{rc}\ j\neq i} q_{ijptn} \right) * \sum_{uql\epsilon Eql_n} Rm_{duql} - M(1-yd_d)$$
$$\forall\ d\epsilon D,\quad \forall\ i\epsilon I_{rc},\quad \forall\ p\epsilon P^{fp},\quad \forall t\epsilon T,\quad \forall\ s\epsilon SC,\quad \forall\ n\ \epsilon\{NT_t\cap NS_s\} \qquad (39)$$

$$\sum_{j\epsilon I_f} q_{ijptn} \geq \left(\sum_{j\epsilon I_{rcc}} q_{ijptn} + \sum_{j\epsilon I_{rdc}} q_{ijptn} + \sum_{j\epsilon I_{fd}} q_{ijptn} + \sum_{j\epsilon I_f} q_{ijptn} - \sum_{j\epsilon I_{rc}\ j\neq i} q_{ijptn} \right) * \sum_{uql\epsilon Eql_n} Rcc_{duql} - M(1-yd_d)$$
$$\forall\ d\epsilon D,\quad \forall\ i\epsilon I_{rc},\quad \forall\ p\epsilon P^{fp},\quad \forall t\epsilon T,\quad \forall\ s\epsilon SC,\quad \forall\ n\ \epsilon\{NT_t\cap NS_s\} \qquad (40)$$

$$\sum_{j\epsilon I_f} q_{ijptn} \geq \sum_{n'\epsilon Na_n} \sum_{j\epsilon I_{rc}} q_{jip(t-1)n'}$$
$$\forall\ i\epsilon I_s,\quad \forall\ p\epsilon P^{rm},\quad \forall t\epsilon T\backslash\{t_1\},\quad \forall\ s\epsilon SC,\quad \forall\ n\ \epsilon\{NT_t\cap NS_s\} \qquad (41)$$

$$\sum_{(i,j)\epsilon\{A^f\cap A^r\}} q_{ijptn} \leq My_i$$
$$\forall i\epsilon\{I^f\cap I^r\}, \forall p\epsilon\{P^{fp}\cap P^{rm}\}, \forall t\epsilon T, \forall s\epsilon SC, \forall n\epsilon\{NT_t\cap NS_s\} \qquad (42)$$

$$\sum_{(i,j)\epsilon\{A^f\cap A^r\}} q_{ijptn} \leq My_j$$
$$\forall\ j\epsilon\{I^f\cap I^r\},\quad \forall\ p\epsilon\{P^{fp}\cap P^{rm}\},\quad \forall t\epsilon T,\quad \forall\ s\epsilon SC,\quad \forall\ n\ \epsilon\{NT_t\cap NS_s\} \qquad (43)$$

$$\sum_{(i,j)\epsilon A^{sf}} q_{ijptn} \geq S_{pi}^{min} y_i$$
$$\forall\ i\epsilon I_s,\quad \forall\ p\epsilon P^{rm},\quad \forall t\epsilon T,\quad \forall\ s\epsilon SC,\quad \forall\ n\ \epsilon\{NT_t\cap NS_s\} \qquad (44)$$

$$\sum_{(i,j)\epsilon A^{sf}} q_{ijptn} \leq S_{pi}^{max} y_i$$
$$\forall\ i\epsilon I_s,\quad \forall\ p\epsilon P^{rm},\quad \forall t\epsilon T,\quad \forall\ s\epsilon SC,\quad \forall\ n\ \epsilon\{NT_t\cap NS_s\} \qquad (45)$$

$$\sum_{j\epsilon I_{fm}} q_{ijptn} + \sum_{j\epsilon I_{dc}, j\neq i} q_{ijptn} \geq D_{pi}^{min} y_i$$
$$\forall\ i\epsilon I_{dc},\quad \forall\ p\epsilon P^{fp},\quad \forall t\epsilon T,\quad \forall\ s\epsilon SC,\quad \forall\ n\ \epsilon\{NT_t\cap NS_s\} \qquad (46)$$

$$\sum_{j\epsilon I_{fm}} q_{ijptn} + \sum_{j\epsilon I_{dc}, j\neq i} q_{ijptn} \leq D_{pi}^{max} y_i$$
$$\forall\ i\epsilon I_{dc},\quad \forall\ p\epsilon P^{fp},\quad \forall t\epsilon T,\quad \forall\ s\epsilon SC,\quad \forall\ n\ \epsilon\{NT_t\cap NS_s\} \qquad (47)$$

$$\sum_{j\epsilon I_{sm}} q_{ijptn} + \sum_{j\epsilon I_{rdc}, j\neq i} q_{ijptn} \geq DR_{pi}^{min} y_i$$
$$\forall\ i\epsilon I_{rdc},\quad \forall\ p\epsilon P^{fp},\quad \forall t\epsilon T,\quad \forall\ s\epsilon SC,\quad \forall\ n\ \epsilon\{NT_t\cap NS_s\} \qquad (48)$$

$$\sum_{j\epsilon I_{sm}} q_{ijptn} + \sum_{j\epsilon I_{rdc}, j\neq i} q_{ijptn} \leq DR_{pi}^{max} y_i$$
$$\forall\ i\epsilon I_{rdc},\quad \forall\ p\epsilon P^{fp},\quad \forall t\epsilon T,\quad \forall\ s\epsilon SC,\quad \forall\ n\ \epsilon\{NT_t\cap NS_s\} \qquad (49)$$

$$\sum_{j\epsilon I_{dc}} q_{ijptn} + \sum_{j\epsilon I_f,\ j\neq i} q_{ijptn} \geq Q_{dpi}^{min} y_i - M(1-yd_d)$$
$$\forall\ d\epsilon D,\quad \forall\ i\epsilon I_f,\quad \forall\ p\epsilon P^{fp},\quad \forall t\epsilon T,\quad \forall\ s\epsilon SC,\quad \forall\ n\ \epsilon\{NT_t\cap NS_s\} \qquad (50)$$

$$\sum_{j\epsilon I_{dc}} q_{ijptn} + \sum_{j\epsilon I_f,\ j\neq i} q_{ijptn} \leq Q_{dpi}^{max} y_i - M(1-yd_d)$$
$$\forall\ d\epsilon D,\quad \forall\ i\epsilon I_f,\quad \forall\ p\epsilon P^{fp},\quad \forall t\epsilon T,\quad \forall\ s\epsilon SC,\quad \forall\ n\ \epsilon\{NT_t\cap NS_s\} \qquad (51)$$

$$\sum_{j\epsilon I_{rdc}} q_{ijptn} + \sum_{j\epsilon I_f} q_{ijptn} + \sum_{j\epsilon I_{rcc}} q_{ijptn} + \sum_{j\epsilon I_{fd}} q_{ijptn} + \sum_{j\epsilon I_{rc}, j\neq i} q_{ijptn} \geq R_{dpi}^{min} y_i - M(1-yd_d)$$
$$\forall\ d\epsilon D,\ \forall\ i\epsilon I_{rc},\ \forall\ p\epsilon P^{fp},\ \forall t\epsilon T,\ \forall\ s\epsilon SC,\quad \forall\ n\ \epsilon\{NT_t\cap NS_s\} \qquad (52)$$

$$\sum_{j\epsilon I_{rdc}} q_{ijptn} + \sum_{j\epsilon I_f} q_{ijptn} + \sum_{j\epsilon I_{rcc}} q_{ijptn} + \sum_{j\epsilon I_{fd}} q_{ijptn} + \sum_{j\epsilon I_{rc}, j\neq i} q_{ijptn} \leq R_{dpi}^{max} y_i - M(1-yd_d)$$
$$\forall\ d\epsilon D,\quad \forall\ i\epsilon I_{rc},\quad \forall\ p\epsilon P^{fp},\quad \forall t\epsilon T,\quad \forall\ s\epsilon SC,\quad \forall\ n\ \epsilon\{NT_t\cap NS_s\} \qquad (53)$$

$$\sum_{j\epsilon I_s} q_{ijptn} \geq \left[\sum_{j\epsilon I_{rc},\ p'\epsilon P^{fp},} q_{jip'tn}\varphi_{dp'p}\left(1-a_{dip't}\right) \right] - M(1-yd_d)$$
$$\forall\ d\epsilon D,\quad \forall\ i\epsilon I_{rcc},\quad \forall\ p\epsilon P^{rm},\quad \forall t\epsilon T,\quad \forall\ s\epsilon SC,\quad \forall\ n\ \epsilon\{NT_t\cap NS_s\} \qquad (54)$$

$$\sum_{j\epsilon I_s} q_{ijptn} \leq \left[\sum_{j\epsilon I_{rc},\ p'\epsilon P^{fp},} q_{jip'tn}\varphi_{dp'p}\left(1-a_{dip't}\right) \right] + M(1-yd_d)$$
$$\forall\ d\epsilon D,\quad \forall\ i\epsilon I_{rcc},\quad \forall\ p\epsilon P^{rm},\quad \forall t\epsilon T,\quad \forall\ s\epsilon SC,\quad \forall\ n\ \epsilon\{NT_t\cap NS_s\} \qquad (55)$$

$$\sum_{j \epsilon I_{dc}} q_{jiptn} = DEC_{pit}$$
$$\forall \ i \epsilon I_{fm}, \quad \forall \ p \epsilon P^{fp}, \quad \forall t \epsilon T, \quad \forall \ s \epsilon SC, \quad \forall \ n \ \epsilon \{NT_t \cap NS_s\} \quad (56)$$

$$\sum_{j \epsilon I_{rdc}} q_{jiptn} \geq DECC_{pit}$$
$$\forall \ i \epsilon I_{sm}, \quad \forall \ p \epsilon P^{fp}, \quad \forall t \epsilon T, \quad \forall \ s \epsilon SC, \quad \forall \ n \ \epsilon \{NT_t \cap NS_s\} \quad (57)$$

Constraint (19) imposes the condition that only one product design must be selected. yd_d adopts value 1 when the product design $d \epsilon D$ is selected. Constraint (20) establishes that if a certain design *d* is selected, all the rate of production of final products associated to designs *d'* must be zero. Constraints (21) and (22) establish the minimum and maximum production rates, respectively, considering whether the entities are incorporated to the network and the product design *d* is selected. Constraints (23) and (24) calculate the inventory of products in production facilities. While constraint (23) determines the inventory at time period *t1*, constraint (24) computes the inventory for time periods *t2*–*tf*. Constraints (25)–(30) are similar to constraints (23) and (24) and determine the inventory of products in distribution, recovery and re-distribution centers. Constraints (31)–(33) determine the safety stocks that should be maintained for a short time period in production, distribution and redistribution centers, respectively, in order to avoid shortages of products due to operation problems of the network. In this work, the safety stocks are computed following the definition given by Kalaitzidou et al. (2015). These authors express the safety stock as a given number of days' equivalent of the material flow exiting from the node to all nodes supply by it. Thus, parameter *dcmf* is the number of days that compose the time period. Constraint (34) describes the relationship between the usage of raw materials during the manufacturing processes with the rate of production of the final product *p*. In this last equation, the utilization factor ($w_{dpp'}$) and the production rate ($p_{dip'tn}$) depend on the product design selected. Eq. (35) establishes the relationship between the maximum availability of manufacturing resources (E_{ri}) and the requirement of resources (λ_{pir}) due to the rates of production employed. Constraint (36) establishes that the flow of recoverable material exiting the first market to recovery centers in a given node *n* of scenario *s* is equal to the final products flows that enter the first market multiplied by a return ratio (RC_{uqt}), which depends on the level of quantity *uqt* considered in the node *n* of the scenario *s*. Constraint (37) states that the flow of products between recovery centers and recycle centers is greater or equal to the flow of product handled by the recovery centers multiplied by the recycling ratio (RRe_{duql}). This rate depends on the product design *d* and the uncertain event *uql*, which is a discrete event related to the uncertain quality of the return flow. Constraints (38)–(40) are similar to constraint (37). Nevertheless, they are established to ensure the flow of products between recovery centers and landfills, recovery and redistribution centers, as well as recovery centers and factories. These flows depend respectively on the disposing ratio (Rdi_{duql}), remanufacturing ratio (Rm_{duql}) and repairing ratio (Rcc_{duql}). These parameters depend on product design selected and on the level of quality *uql* considered in the node *n* of scenario *s*. It is worth noting that constraints (37)–(40) are only active for the product design selected. Constraint (41) states that the flow of products between suppliers and plants at time *t* is greater or equal to the flow of product recovered by the recycle center a time *t-1*.

Constraints (42) and (43) allow the existence of outgoing and incoming flows between two network entities if the considered entity belongs to the network. Constraints (44)–(53) establish the upper and lower bounds that are imposed for the flow of raw materials/final products from suppliers, distribution centers, redistribution centers, plants and recovery centers. While constraints (44)–(49) are active if the entities are open, constraints (50)–(53) are active depending also on the product design selected. Constraints (54) and (55) establish the relationship between the flows of recyclable products entering to the recycle centers to the raw materials entering to the suppliers. This relationship depends on the conversion factor $\varphi_{dpp'}$ and the recycling performance factor a_{dipt}, that are conditional to the product design. In addition, Eqs. (54) and (55) are active for a given design *d*. Constraint (56) states that the flow of final products arriving at the first market from distribution centers is equal to customer demand. Finally, Eq. (57) establishes that the flow of final products arriving at the second market from re-distribution centers is greater or equal to customer demand for remanufactured products. It is worth noting that, in the same way that other authors did (Kalaitzidou et al., 2014; 2015), in the model is assumed that the first market demand is known and it is satisfied with equality. On the other hand, the second market demand is formulated as an inequality constraint because in the formulation the quality and quantity of the materials/products that flow in the reverse supply chain are considered as uncertain parameters. In addition, the different product designs influence the different flows of materials in the reverse network. Therefore, in the model, what is imposed for the second market is the fulfillment of a minimum demand, which practically must be feasible for all the possible scenarios and designs considered.

5. Example

The real medium-size case study of a CLSC introduced by Kalaitzidou et al. (2015) was considered and modified in order to illustrate the application of the PNDUC approach. Possible states of the uncertain parameters, cost associated with different product designs and revenues obtained by selling new, remanufactured and recycled products are some of the additional data that are included to test the approach proposed. 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*) (see Table 1).

The profit of the organization is optimized considering the product design and network structure. Four raw materials (*rm1* to *rm4*) are used to manufacture ten final products (*p1* to *p10*). The planning horizon is composed of three years of four trimesters each one. Transportation CO_2 emissions costs for moving raw materials and final products are also considered.

Three possible levels for the uncertainty for quality and quantity of return flows are considered (low, medium and high quality: *uql1, uql2* and *uql3*; and low, medium and high quantity: *uqt1, uqt2* and *uqt3*). Three alternative product designs are also modeled (*d1, d2* and *d3*). *d2* is a design that adopts a design philosophy between the design for recycling (DfRc: *d1*) and the design for remanufacturing (DfRm: *d3*). Table 2 shows the ratio of recycling, repairing, remanufacturing and disposing that depend on the product design and the levels of quality of the return flows considered. Table 3 illustrates the return ration of final products considering the three possible levels for the return quantity. Thus, considering the design *d1* and the level of quality *uql1*, 25% and 30% of the total flow of recoverable material are the ratios of recyclable products entering to the recycle centers and the scrapped products entering the disposal sites, respectively. In addition, 35% and 10% are the ratios of the remanufacturable and repairable products entering the redistribution centers and the production facilities, respectively. As it can be seen in Table 2, the different designs influence the flows

Table 1
Network super-structure.

Possible locations	Suppliers (*s*)	Factories (*f*) Distribution Centers (*dc*) Recovery Centers (*rc*) Redistribution Centers (*rdc*)	First Market (*fm*)	Second Market (*sm*)	Final Disposal (*fd*)	Recycle Center (*rcc*)
Austria (AT)		*	*			
Belgium (BE)		*	*			
Bulgaria (BG)	*			*		
Czech Republic(CH)			*			
Denmark (DK)		*	*			
Finland (FI)		*	*			
France (FR)		*	*	*	*	*
Germany (DE)			*		*	*
Greece (GR)		*	*			
Ireland (IE)		*	*			
Italy (IT)		*	*	*	*	*
Netherlands (NL)		*	*			
Norway (NO)		*	*	*		
Poland (PL)			*			
Portugal (PT)		*	*			
Romania (RO)	*					
Russia (RU)	*					
Spain (ES)		*	*			
Sweden (SE)		*	*			
Switzerland (CH)		*				
Turkey (TR)	*		*			
United Kingdom (UK)		*	*	*		
Ukraine(UA)	*					

Table 2
Recycling ratio (RRe), disposing ratio (Rdi), repairing ratio (Rcc) and remanufacturing ratio (Rm).

	Prob.	*RRe [%]*			*Rdi[%]*			*Rcc[%]*			*Rm[%]*		
		d1	*d2*	*d3*	*d1*	*d2*	*d3*	*d1*	*d2*	*d3*	*d1*	*d2*	*d3*
Low (uql1)	*0.2*	25	17	10	30	45	55	35	23	15	10	15	20
Medium (uql2)	*0.45*	27	20	13	20	35	45	38	25	17	15	20	25
High (uql3)	*0.35*	29	23	16	10	25	35	41	27	19	20	25	30

Table 3
Return ratio (RC).

	Prob.	*RC [%]*
Low (uqt1)	*0.4*	*0.3*
Medium (uqt2)	*0.35*	*0.45*
High (uqt2)	*0.25*	*0.6*

of the recovered products. For example, considering the design *d1*, the ratio of products that flow from recovery centers to recycle centers (parameter *RRe*) is greater than the same ratio associated with the other designs. When the design *d3* is considered, the ratio of products that flow from the recovery centers to factories for its re-manufacturing (parameter *Rm*) is greater than the same ratio for the other designs. The previously mentioned occurs in any of the levels of quality considered. In addition, the distinct designs are related to different levels of usage of the raw materials in the manufacturing stage and dissimilar amounts of recovery of the raw materials (see Tables B26 and B27 of Appendix B). Additional data related to the uncertain parameters, the different product design and the CO_2 emission is provided in Appendix B.

6. Results

To illustrate the relevance of the proposed approach, the formulation was coded in the optimizer software called GAMS (release 24.7.1) and the case study was solved taking into account different conditions. All computations were run with CPLEX 12.7, on a HP Z800 workstation with Intel Xeon x5650 2.66 GHz and 32GB RAM memory for a 0.01 gap tolerance.

6.1. Scenario reduction approach

The representation of the original problem involves a two-layered tree of 9 scenarios (s_1 to s_9) with 28 nodes (1 root node and 3 nodes for each scenario). It is important to note that, while the three nodes that compose a given scenario are associated with the same occurrences of the uncertain parameters, the nodes explicitly represent different values for other model parameters that change during the planning horizon (such as the demand). The resulting problem is a complex problem in computational terms. Thus, in order to reduce such complexity a scenario reduction algorithm is used guaranteeing a reasonably good approximation of the original problem (Growe-Kuska et al., 2003). The reduction algorithms exploit a certain probability distance of the original and the reduced probability measure (Dupacova et al., 2003; Growe-Kuska et al., 2003). Therefore, the scenario deletion will occur if scenarios are close or have small probabilities. Several algorithms for reducing scenarios are accessible in the GAMS library SCENRED (GAMS/SCENRED Documentation, 2013).

In this work, the algorithm applied is a mix of fast backward and forward algorithms that operates over the original tree. Table 4 shows the results obtained for solving the problem considering the approach with objective function OFCVaRp and taking into account different levels of scenario reduction. The performance measure OFCVaRp is used in this section due to among all the performance measure considered, OFCVaRp is the one that more time consumes.

From the analysis of the results obtained for different levels of scenario reduction, it can be noted that the discretization of the uncertain parameters and the non-uniformity of the probability‘s values of each uncertain event produce that the number of scenarios preserved by the scenario reduction algorithm varies dis-

Table 4
Results for different levels of scenario reduction.

% of information of the original problem	Scenarios	*Nodes*	OFCVaRp	*CPU Time [s]*
100	9	28	-	600000
90	7	22	2179997	505091
80	5	16	2189387	324319
70	3	10	2108402	41442
60	3	10	2108402	41637

- no solution found before the time limit of 600,000 s.

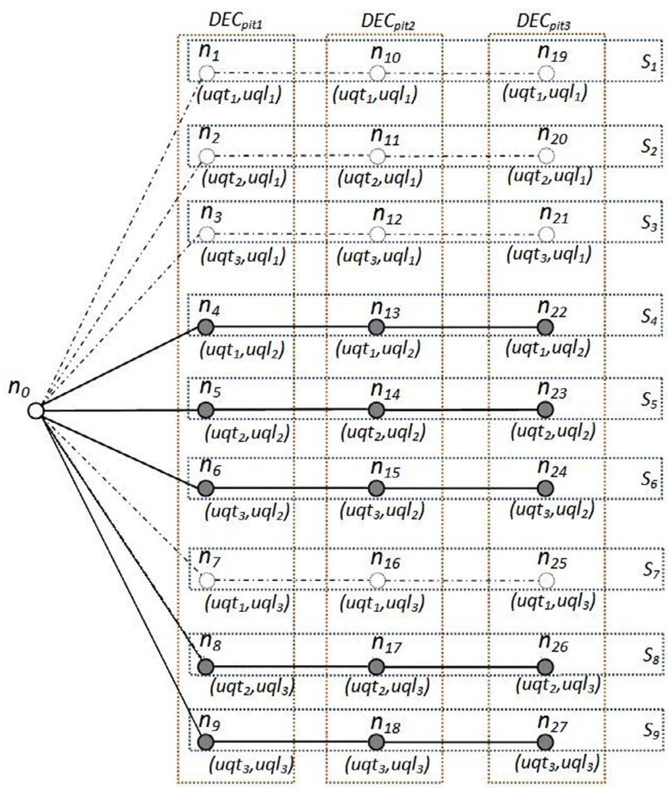

Fig. 2. Scenario tree with three periods and three events for two uncertain parameters (quality and quantity return).

creetly with respect to the amount of information that is desired to maintain after applying the scenario reduction algorithm. It is worth remarking that, for the example addressed considering the events and probabilities described, the same reduced tree (composed of 3 scenarios) is obtained to preserve 60% and 70% of the original information contained in the tree.

From the results shown in Table 4, and in order to maintain a suitable level of information of the original problem and a computational cost of size according to the problem, in this work it is used a reduced tree obtained by applying the scenario reduction algorithm over the original tree maintaining 80% of the original information contained in the tree. This selection is supported by the fact that the difference between the values of the objective function for 90% and 80% is small and the main characteristics of both solutions (such as network structure and product design) are equals. Fig. 2 shows the two-layered tree obtained after applying the reduction algorithm. The compact tree is composed of 5 scenarios (s_4, s_5, s_6, s_8 *and* s_9) with 16 nodes (1 root node and 5 nodes in the each time period). The parameters associated with the risk measure, αp and β, are equal to 0.5 and 1.5, respectively. Thus, these values 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.

6.2. Problem characteristics analysis with different objective functions

Table 5 shows the different cases solved considering different conditions for product design, network structure and the quality and quantity events. Cases 0–2 are determinist instances where the quality and quantity of return flows are obtained as the average values of the events associated with each parameter (*uql1 to uql3* and *uqt1 to uqt3)* for the product design *d2*. The average values of the parameters Recycling ratio (*RRe*), disposing ratio (*Rdi*), repairing ratio (*Rcc*), remanufacturing ratio (*Rm*) and Return ratio (*RC*) are shown in Table 6.

In comparison with Case 0, Cases 1 and 2 involve the selection of the product design used in the CLSC. Furthermore, while Case 1 considers that the network structure is fixed (as defined in Case 0, NSC0), Case 2 optimizes the network structure simultaneously with the product design. Cases 3–8 take into account the uncertain conditions of the problem by mean of the compact tree composed by 5 scenarios determined in the previous section. Cases 3–5 consider the objective function as the expected profit (OFEP: *ER- EOC-SCSC*), and Cases 6–11 consider the OFCVaRp as the performance measure. It is important to note that Cases 1, 4 and 7 use the network structure obtained in Case 0 as reference (NSC0) because it is the network design corresponding to the solution that is obtained with a basic model built considering the existence of a single product design and deterministic parameters associated with the flow of returned products. In addition, Cases 0, 3 and 6 use the product design *d2* as reference because it is a compromise design between *d1* and *d3*. Summarizing, Cases 2, 5 and 8 solve simultaneously network and product design problems, while the other cases only take into account one problem at a time. Cases 9–11 uses the network structure obtained in Case 8 considering the original tree composed by 9 scenarios. Each one of the Cases 9–11 takes into account a different product design. Finally, while Case 12 considers the performance measures OFERSP, Cases 13–15 take into account the objective function OFCVaRrsp. The results obtained for Cases 0–15 are shown in Tables 7–10. The computational statistics for the cases solved are given in Appendix C.

Table 7 shows the solutions obtained for Cases 0–11. The cases consider separately, and then collectively, the problems of product and network design for three different objective functions. From Table 7, it can be observed that the cases where the two problems are considered simultaneously (Cases 2, 5 and 8) always obtain better or equal objective function values when compared to cases where the problems are studied separately. In Cases 2 and 5, the improvement is directly connected to the profit and expected profit increases, respectively. The profit in Case 2 is 5.23% and 0.1% better than the profit in Cases 0 and 1, respectively. The expected profit in Case 5 is 5.26% and 0.69% better than the expected profit in Cases 3 and 4, respectively.

In Case 8, the improvement is associated with achieving a solution that avoids important profit decreases considering the scenarios resulting from applying the scenario reduction algorithm. In order to quantify the effects of using a risk measure in a comprehensive context of the problem (considering the product and network designs), Table 7 shows, in percentage, the difference between the

Table 5
Cases characteristics.

Case	OF	Network Structure	Considered Design	Quality Events	Quantity Events	Scenarios
0	Profit	–	d2	Av	Av	1
1	Profit	NSC0	d1-d3	Av	Av	1
2	Profit	–	d1-d3	Av	Av	1
3	OFEP	–	d2	uql1-uql3	uqt1-uqt3	5
4	OFEP	NSC0	d1-d3	uql1-uql3	uqt1-uqt3	5
5	OFEP	–	d1-d3	uql1-uql3	uqt1-uqt3	5
6	OFCVaRp	–	d2	uql1-uql3	uqt1-uqt3	5
7	OFCVaRp	NSC0	d1-d3	uql1-uql3	uqt1-uqt3	5
8	OFCVaRp	–	d1-d3	uql1-uql3	uqt1-uqt3	5
9	OFCVaRp	NSC8	d1	uql1-uql3	uqt1-uqt3	9
10	OFCVaRp	NSC8	d2	uql1-uql3	uqt1-uqt3	9
11	OFCVaRp	NSC8	d3	uql1-uql3	uqt1-uqt3	9
12	OFERSP	–	–	uql1-uql3	uqt1-uqt3	5
13	OFCVaRrsp	–	d1-d3	uql1-uql3	uqt1-uqt3	5
14	OFCVaRrsp	NSC13	d2	uql1-uql3	uqt1-uqt3	5
15	OFCVaRrsp	NSC13	d3	uql1-uql3	uqt1-uqt3	5

OFEP: Expected Profit = $ER - EOC - SCSC$
Av: Average values of the uncertain events
–: Network structure determined by the model
NSC0: Network Structure obtained in Case 0
NSC8: Network Structure obtained in Case 8
NSC13: Network Structure obtained in Case 13

Table 6
Recycling ratio (*RRe*), disposing ratio (*Rdi*), repairing ratio (*Rcc*), remanufacturing ratio (*Rm*) and *return ratio (RC) used in Cases 0–2*.

RRe [%]	*Rdi[%]*	*Rcc[%]*	*Rm[%]*	*RC [%]*
20	*35*	*25*	*20*	*0.45*

expected profit of each case and the profit of the scenario with the most unfavorable conditions of the scenarios taken into account in the reduced tree. This parameter expresses the maximum profit decrease, in percentage, that it can occur when the worst scenario takes place. From the results obtained and considering the profit decrease, it is worth remarking that the percentage of profit decrease of all cases where the risk is not considered (Cases 3–5) is bigger than the percentage of Case 8. The percentage of profit decrease of Case 8 (3.1%) is less than the ones obtained for Cases 6 and 7. In addition, in order to achieve a solution able to avoid a certain level of risk, the network structure selected in Case 8 is different from those obtained in the other cases. The solution achieved for Case 8 is based on the product design *d1* and a network structure with facility costs smaller than the ones of the other cases (Cases 0–7). Thus, it can be concluded that the join consideration of product and network design problems and the explicit consideration of a risk measure over the profit lead to a solution that limits the profit decreases while maintaining an adequate expected profit level. The solution obtained in Case 8 presents an expected profit that is 1.23% greater than the profit of the determinist Case 2 and 1.37% lower than the expected profit of Case 5 where the risk is not considered.

From the results obtained for Case 8, it can be remarketed that the products for the first market are manufactured using 2.13% of raw material coming from the recycling of products and 15.69% of the repair of final products. If only the existence of the forward supply chain would be considered, the amount of virgin raw material required to produce the same quantity of final products as in the solution of case 8 should increase by 21.44%. The aforementioned clearly allows to visualize the advantage of using the proposed model instead of a simplified model associated only with the forward network.

Table 7
Results for Cases 0–11.

Case	Design	Facility Costs [rmu]	Reverse Costs [rmu]	Total Revenues [rmu]	Revenues Suppliers [rmu]	Revenues Factories [rmu]	Revenues Second Market [rmu]	OF	Profit Decrease [%]
0	d2	1,193,250	253,089	8,070,652	8180	50,664	583,679	1,355,975	0
1	d1*	1,162,500	250,814	7,946,288	9515	73,254	435,367	1,429,434	0
2	d1*	1,153,500	258,839	7,946,087	9362	73,206	435,367	1,430,867	0
3	d2	1,193,250	239,712	8,071,220	8036	49,006	586,028	1,391,326	4.2
4	d1*	1,134,500	241,318	7,956,801	9047	74,471	445,131	1,458,441	3.7
5	d1*	1,196,500	235,620	7,959,234	9016	76,936	445,131	1,468,557	3.2
6	d2	1,193,250	239,746	8,061,625	8524	49,202	575,726	1,841,926	5.1
7	d1*	1,134,500	241,071	7,951,221	9564	74,769	438,737	2,147,721	4.4
8	d1*	1,099,500	235,329	7,951,216	9594	74,734	438,737	2,189,388	3.1
9	d1	1,099,500	235,927	7,937,334	9520	74,270	425,392	2,117,824	16.8
10	d2	1,164,500	235,902	8,046,631	8426	49,008	561,045	1,746,178	17.8
11	d3	1,223,500	228,268	8,164,904	4938	33,555	6,98,258	1,549,572	17.2

All values are expressed in currency units [c.u.].
*product design determined by the model.
Reverse Cost: Cost connected with the activities of recovery, remanufacturing, repairing, disposing and recycling.
Revenues Suppliers: revenues for returning materials to suppliers.
Revenues Factories: revenues for returning materials to factories.
Revenues Second Market: revenues for selling products to the second market.

Table 8
CLSC structure for Cases 2, 5 and 8.

Suppliers (*s*)	Factories (*f*)			Distribution Centers (dc)		Recovery Centers (rc)			Recycle Centers (rcc)		Final Disposal (fd)	Redistribution Centers (rdc)	
Cases	Cases			Cases		Cases			Cases		Cases	Cases	
2, 5 & 8	**2**	**5**	**8**	**2, 5 & 8**		**2**	**5**	**8**	**2**	**5 & 8**	**2, 5 & 8**	**2**	**5 & 8**
RU	IT	IT	IT	IT	FI	DK	DK	DK	FR	FR	FR	BE	BE
TR	ES	NL	IE	FR	PT	BE	BE	BE	IT	IT	IT	CH	
BG	GR	GR	GR	IE	BE	GR	GR	GR		DE			
RO	DK	DK	DK	GR	CH	FR		IE					
	FI	FI	FI	DK									

Table 9
Results for Cases 12–15.

Case	Design	Facility Costs [rmu]	Reverse Costs [rmu]	Total Revenues [rmu]	Revenues Suppliers [rmu]	Revenues Factories [rmu]	Revenues Second Market [rmu]	OF
12	d1*	1,828,400	265,440	7,972,780	11,140	101,520	431,975	112,660
13	d1*	1,749,800	263,945	7,962,171	11,128	101,520	421,365	243,383
14	d2	1,818,050	257,044	8,068,132	9932	66,804	563,243	165,802
15	d3	1,883,000	249,605	8,180,239	5905	45,809	700,373	111,801

All values are expressed in currency units [c.u.].
*product design determined by the model.
Reverse Cost: Cost connected with the activities of recovery, remanufacturing, repairing, disposing and recycling.
Revenues Suppliers: Revenues for returning materials to suppliers.
Revenues Factories: Revenues for returning materials to factories.
Revenues Second Market: Revenues for selling products to the second market.

Table 10
CLSC structure for Cases 12 and 13.

Suppliers (s)	Factories (f)		Distribution Centers (dc)		Recovery Centers (rc)		Recycle Centers (rcc)	Final Disposal (fd)	Redistribution Centers (rdc)	
Cases	Cases		Cases		Cases		Cases	Cases	Cases	
12 & 13	**12**	**13**	**12**	**13**	**12**	**13**	**12 &13**	**12 & 13**	**12**	**13**
RU	IT	IT	ES-IT	ES-IT	IT-FR	IE	IT	IT	CH	BE
TR	FR	FR	FR-SE	FR-SE	SE-IE	DK				
BG	IE	GR	IE-NL	IE-NL	DK-FI	BE				
RO	GD	DK	DK-FI	DK-FI	PT-BE					
UA	FI	FI	PT-BE	PT-BE	AT					
	UK	UK	CH-NO	CH						

Finally, considering the 9 scenarios of the original tree, the network structure achieved in Case 8 and the product designs *d1* to *d3* (Cases 9–11), it can be observed that the percentage of profit decrease rises above 16.8% because these cases include scenarios previously not taken into account. Nevertheless, it is important to point out that when the network structure and the product design obtained in Case 8 are used (Case 9), the best expected profit and the percentage of profit decrease (143,926[rmu] and 16.8%, respectively) are obtained. In addition, the values of the objective function and the expected profit are only 0.95% and 3.27% lower than the values achieved in Case 8.

Fig. 3 shows the relation between the solutions of Cases 0–2, 0–5 and 0–8, where the deterministic Case 0 is adopted as the reference instance. Case 5 shows the greatest growth in revenues for returning materials and inventory costs, as well as the largest decrease in transportation, handling, purchasing and emissions costs. Case 8 has characteristics very similar to those of Case 5 when considering purchasing, emissions and inventory costs. However, Case 8 presents an increase in production costs, while Cases 2 and 5 show a reduction in those costs. On the other hand, Case 2 is the only one where the costs associated with CO_2 emissions are increased.

Fig. 4 shows the relation between the solutions of Cases 2 and 5 versus the solution of Case 8. Considering the Cases 2–8, it can be seen that, the revenues obtained for returning material to the forward network in Case 8 are greater than in Case 2. In addition, while the costs associated with the purchase of materials and the CO_2 emissions are lower than in Case 2, transport, production and inventory costs are higher. It is important to note that the solution obtained in Case 8 has better environmental characteristics than the solution achieved in Case 2 because the lower costs associated with the purchase of materials and CO_2 emissions. Taken into account Cases 5–8, both solutions maintain similar costs of inventory, purchase of raw materials and CO_2 emissions. However, the solution obtained in Case 8 limits the revenues for returning materials and increases the costs of transport, handling and production.

In terms of supply chain network, Table 8 shows the network structures obtained for Cases 2, 5 and 8. Comparing with Cases 2 and 5, the network structure for Case 8 differs in the location and number of entities, such as factories, recovery centers, recycle centers and redistribution centers. For example, while the number of factories is the same for the three cases (with different location), the recovery centers differ in number and location. In particular, the main alterations between the solutions of Cases 5 and 8 correspond to the location of factories (while in Case 5 a factory is opened in NL, in Case 8 a factory is opened in IE) and the number of recovery centers (Case 8 opens a recovery center in IE, which is added to the group of centers opened in Case 5). Fig. 5 shows the network structure obtained for Case 8.

In an effort to further highlight the importance of the model, the results obtained for Cases 12–15, which consider the objective functions OFERSP and OFCVaRrsp, are shown in Tables 9 and 10,

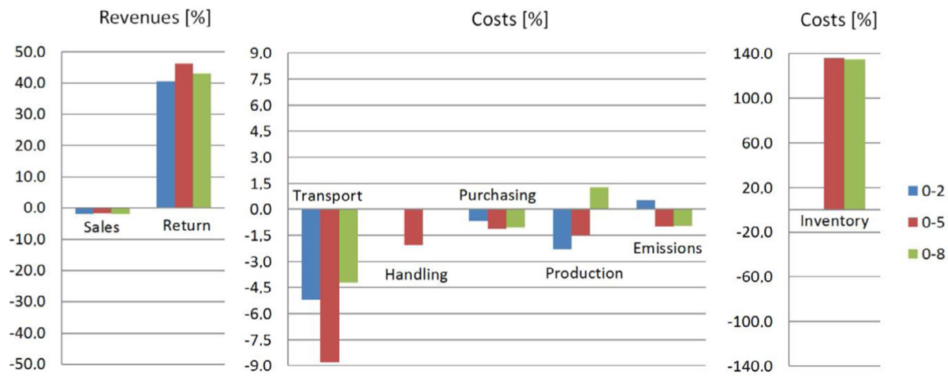

Fig. 3. Relationship between the solutions of Cases 0–2, 0–5 and 0–8.

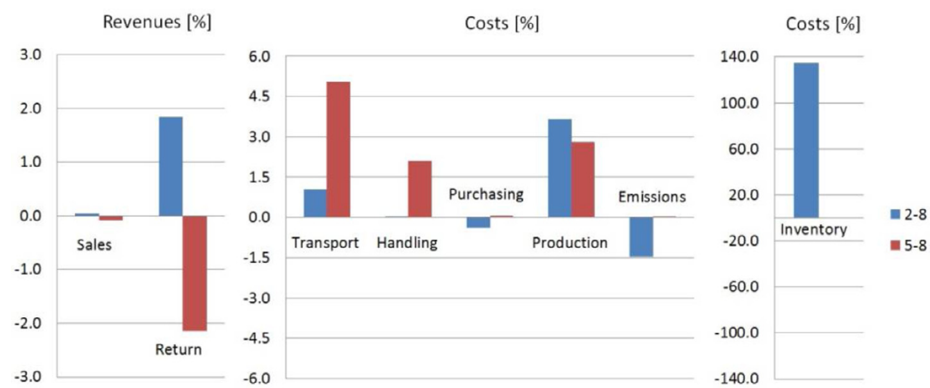

Fig. 4. Relationship between the solutions of Cases 2–8 and 5–8.

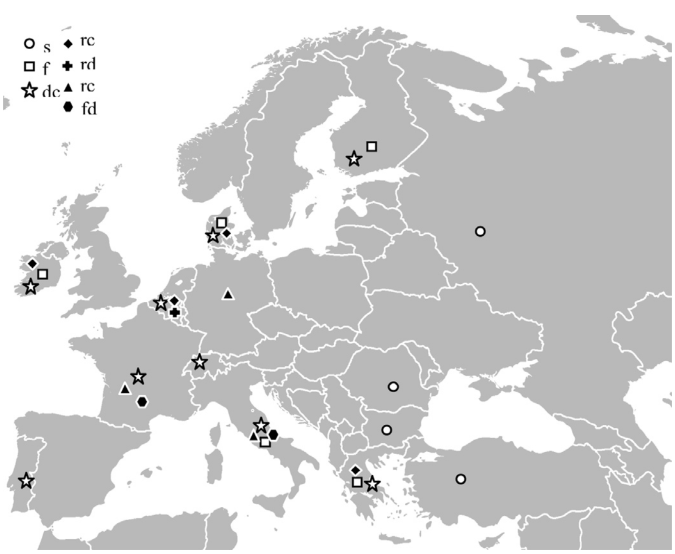

Fig. 5. CLSC structure for Case 8.

as well as Fig. 6. Table 9 shows the solutions obtained when Cases 12–15 are solved. The solutions found in Cases 12 and 13 differ mainly in the facility costs and in the revenues for selling products to the secondary market. The expected revenues achieved by returning materials to suppliers and factories are very similar (Case 12: 112,660 [rmu], Case 13: 112,648 [rmu]). However, in Case 13, the level of expected revenues is obtained with lower facility costs than in Case 12. The expected profits for all cases of Table 9 are equal to 0.

On the other hand, when designs *d2* and *d3*, as well as the network structure obtained in Case 13 are considered (Cases 14 and 15), the expected revenues achieved are lower than in Case 13 (Case 14: 76,736 [rmu]; Case 15: 51,714 [rmu]). Furthermore, Cases 14 and 15 present revenues for selling products to the secondary market greater than in Case 13.

Fig. 6 shows the relation between the solutions of Cases12 and 13. From Fig. 6, it can be seen that, the revenues obtained when selling products (to first and second markets) in Case 13 are lower than in Case 12. In addition, in comparison with Case 12, Case 13 presents lower handling and purchasing costs, as well as greater transport, production, CO_2 emissions and inventory costs. In comparison with the expected revenues achieved by returning materials to suppliers and factories in Case 8, the revenues of Case 13 are 33.6% greater. With respect to the expected revenues maximization, the usage of the objective function that quantify the risk of revenues leads to a solution with lower revenues of the second market and greater transportation and inventory costs. Nevertheless, the expected revenues of both cases are similar.

In terms of supply chain network, Table 10 shows the network structures obtained for Cases 12 and 13. Comparing with Case 12, the network structure for Case 13 differs in the location and number of entities, such as factories, distribution centers, recovery centers and redistribution centers. The limited number of recovery centers in the solution achieved in Case 13 represents the most relevant difference when compared to the solution achieved in Case 12.

6.3. Managerial insights

The study developed allows us to derive the following managerial insights:

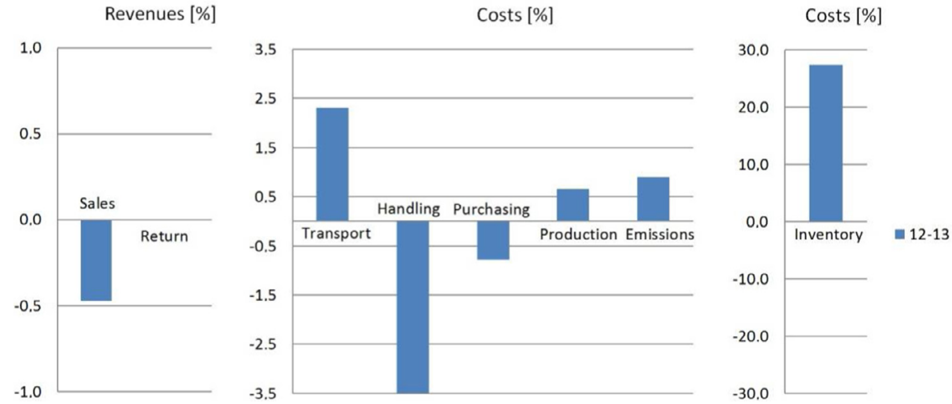

Fig. 6. Relationship between the solutions of cases 12 and 13.

- The join consideration of product and network design problems has a high impact on the network profit and revenues;
- Revenues achieved by returning materials to suppliers and factories can be substantially increased when the revenues expected value is maximized or the risk of revenues is considered;
- A bad selection of the product design can lead to a high decrease in expected revenues achieved by returning materials to suppliers and factories.

From the results it can be seen that when the objective function that measures the profit risk is used, trade-off solutions between costs and revenues are obtained. In addition, the solutions are characterized by avoiding decreases in profits when the worst conditions of the uncertain parameters are reached while maintaining good levels of expected profit.

When the revenues and profit risks are taken into account, the design for recycling (*d1*) is the most valuable design. The CLSC associated with the design *d1* is characterized by having low facility costs. When designs *d2* and *d3* are considered with the best network structure obtained for OFCVaRrsp, it can be seen that while the expected revenues for selling products to the secondary market increase, the expected revenues achieved by returning materials to suppliers and factories decline. Thus, a bad selection of the product design can lead, in the worst case, to an expected revenues achieved by returning materials to suppliers and factories of 54.09% lower. Nevertheless, in both cases (with product design *d2* and *d3*), the total revenues of the network increase.

When design *d3* are considered with the best network structure obtained for OFCVaRrsp, it can be seen that this design leads to a solution that has the highest revenues for selling products to the second market.

Revenues with materials return to suppliers and factories can be increased when the revenues expected value is maximized or the risk of revenues is considered. However, in these cases, the solutions have higher facility and operating costs than the cases with objective functions based on the total profit of the network. In addition, costs increase to such high levels that the overall operation of the chain is at the limit of its economic viability.

7. Conclusions

The present work is a first attempt to fill a gap in the join management of three relevant aspects in closed loop supply chain: product and network design while accounting for the risk associated with uncertainty on the return flows of products (in quantity and quality). To address this problem this paper introduces a two-stage stochastic mixed integer linear framework that considers alternative selection of product designs and network structures, as well as considers the profit risk due to the uncertain quality and quantity of the return flows. The model performance function is based on the conditional value at risk (CVaR) concept applied to profit. The risk management is oriented to assure that the uncertainty on the quality and quantity of the return flows does not turn aside the supply chain behavior from the business goals. Thus, the approach is able to avoid that variations on the quality and quantity of the return flows produce significant changes on the economic performance of the network.

From the results, it can be stated that the product and network design decisions are highly coupled given that the characteristics of most of the network entities (for example, inventory and processing capacities) depend on the product design selected. The advantage of jointly considering the problems of network and product design in a context in which the risk is controlled was shown. Thus, the proposed approach leads to solutions that substantially limit the profit decreases while maintaining an adequate expected profit levels.

As future work, several points can be identified. An area for additional research is the development of a multi-stage stochastic framework considering further important uncertain parameters such as demand, supply and costs. Furthermore, alternative solution methods should be analyzed in order to improve the exploration of the solution space and reduce the solution computational effort. Sensitivity analyses on key parameters of the objective function should be also explored in order to be able better understand the different objective function components. Thus, as future work, and related to the practical analysis of the case study, a Pareto-surface could be built varying the parameter β in order to be able to show the relevance in the CLSC of the risk measurement against the expected values. Finally, more alternative product designs and the selection of the designs for each product are to be analyzed.

Acknowledgments

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Appendix A

Sets

A^f set of arcs between entities belonging to the forward network, $\{(i,j): (i\in I_s, j\in I_f) \vee (i\in I_f, j\in I_{dc}) \vee (i\in I_{dc}, j\in I_{fm}) \vee (i\in I_c, j\in I_{rc})\}$

A^{fmrc} $\{(i,j): (i\in I_{fm}, j\in I_{rc})\}$,

A^r set of arcs between entities belonging to the reverse network, $\{(i,j): (i\in I_{fm}, j\in I_{rc}) \vee (i\in I_{rc}, j\in I_{rcc}) \vee (i\in I_{rc}, j\in I_{fd}) \vee (i\in I_{rc}, j\in I_f) \vee (i\in I_{rc}, j\in I_{rdc}) \vee (i\in I_{rcc}, j\in I_s) \vee (i\in I_{rdc}, j\in I_{sm})\}$,

A^{rc} $\{(i\in I_{rc}, j\in I_{rcc}) \vee (i\in I_{rc}, j\in I_{rdc}) \vee (i\in I_{rc}, j\in I_{fd}) \vee (i\in I_{rdc}, j\in I_{sm}) \vee (i\in I_{rcc}, j\in I_s)\}$,

A^{rf} $\{(i,j): (i\in I_{rc}, j\in I_f) \vee (i\in I_{rcc}, j\in I_s)\}$,

A^{sf} set of arcs between suppliers and factories, $\{(i,j): (i\in I_s, j\in I_f)\}$

Eql discrete events related to the quality levels of the return flows,

Eql_n discrete events related to the quality levels of the return flows of node n,

Eqt discrete events related to the quantity levels of the return flows,

Eqt_n discrete events related to the quantity levels of the return flows of node n,

I supply chain entities,

I_{dc} distribution centers,

I_{dp} decomposition centers,

I_f factories,

I^f set of entities belonging to the forward network, $\{I_s \vee I_f \vee I_{dc} \vee I_{fm}\}$

I_{fd} final disposal,

I^{fi} set of entities with storage capacity belonging to the forward network, $\{I_f \vee I_{dc}\}$

I_{fm} first market,

I^r set of entities belonging to the reverse network, $\{I_{fm} \vee I_{sm} \vee I_{rc} \vee I_{rdc} \vee I_{fd} \vee I_{rcc}\}$

I_{rc} recovery centers,

I_{rcc} recycle centers,

I_{rdc} re-distribution centers,

I^{rf} set of entities that make the link between the reverse and forward networks $\{I_{rc} \vee I_{rcc}\}$,

I^{ri} set of entities with storage capacity belonging to the reverse network, $\{I_{rc} \vee I_{rdc}\}$

I_s suppliers,

I_{sm} second market,

N nodes of the scenario tree. n0 is the root note that represents the initial state of the problem at the beginning ofthe planning horizon,

Na_n node of the scenario tree that is father of node n,

NS_s nodes belonging to the scenario s,

NT_t set of nodes associated with time period t,

P products,

P^{fp} final products,

P^{rm} raw material,

R manufacturing resources,

SC $SC = \Omega_{nt1}\ \Omega_{nt2}\ \Omega_{nt3}\ ....\ \Omega_{ntf}$, set of scenarios. Each scenario is formed by a given sequence of events from the root node until a particular leaf node at the last time period.

T time units,

Ω combination of events belonging to Eql and Eqt $\{(uql, uqt): uql\in Eql, uqt\in Eqt\}$,

Ω_{nt} combination of events belonging to Eql and Eqt $\{(uql, uqt): uql\in Eql, uqt\in Eqt\}$ associated with node n at time period t,

Parameters

a_{dipt} recycling performance factor for product p at recycle center i in design d

C_i^D fixed cost of establishing distribution center i

C_i^{DR} fixed cost of establishing redistribution center i

C_i^{Di} fixed cost of establishing disposal site i

C_i^S fixed cost of establishing relationship with supplier i

C_{id}^P fixed cost of establishing plant i considering product design d

C_{id}^R fixed cost of establishing recovery center i considering product design d

C_{id}^{Re} fixed cost of establishing recycling center i considering product design d

C_{pi}^{DH} unit handling cost for material p at node $i \in I_{dc}$

C_{pi}^{DRH} unit handling cost for material p at node $i \in I_{rdc}$

C_{pi}^{Di} unit disposal cost for disposable product p at node $i \in I_{fd}$

C_{pi}^{RM} unit remanufacturing cost for remanufacturable product at node $i \in I_{rc}$

C_{pi}^{RP} unit repairing cost for repairable product p at node $i \in I_{rc}$

C_{pi}^{RV} unit recovering cost for recoverable product p at node $i \in I_{rc}$

C_{pi}^{Re} unit recycling cost of raw material p at node $i \in I_{rcc}$

C_{pi}^S unit purchase price of material p from supplier node $i \in I_s$

C_{pij}^T unit transportation cost of product p from node $i \in I$ to node $j \in I$

C_{pit}^{IDR} unit inventory cost for material p at node $i \in I_{rdc}$ during time period t

C^{IP}_{pit}	unit inventory cost for material p at node $i \in I_f$ during time period t
$dcmf$	days corresponding to the time period considered for the material flow.
$DECC_{pit}$	minimum demand for product p by the second market node $i \in I_{sm}$ at time period t
DEC_{pit}	demand for product p by the first market node $i \in I_{fm}$ at time period t
D^{max}_{pi}	maximum capacity of distribution of product p of distribution center i
D^{min}_{pi}	minimum capacity of distribution of product p of distribution center i
DR^{max}_{pi}	maximum capacity of re-distribution of product p of re-distribution center i
DR^{min}_{pi}	minimum capacity of re-distribution of product p of re-distribution center i
ec^f	emission cost for forward network
ec^r	emission cost for reverse network
E_{ri}	total rate of availability of resource r of plant i.
hp	number of days equivalent of material flow delivered for plants and/or distribution centers.
hrd	number of days equivalent of material flow delivered for re-distribution centers.
M	large number
Pb_s	occurrence probability of scenario s. $Pb_s = \{(P_{uql}P_{uqt})_{\Omega nt1}\ (P_{uql}P_{uqt})_{\Omega nt2}\ (P_{uql}P_{uqt})_{\Omega nt3}$ ....$(P_{uql}P_{uqt})_{\Omega nT})_{\Omega sT}$
P^{max}_{pid}	maximum production capacity of product p of each production plant i of design d
P^{min}_{pid}	minimum production capacity of product p of each production plant i of design d
P_{uql}	occurrence probability of the return quality level uql∈Euql
P_{uqt}	occurrence probability of the return quantity level uql∈Euqt
Q^{max}_{dpi}	maximum rate of flow of product p of plant i considering product design d.
Q^{min}_{dpi}	minimum rate of flow of product p of plant i considering product design d.
Rcc_{duql}	remanufacturing ratio
RC_{uqt}	return ratio of the recoverable products from the first customers markets
Rdi_{duql}	disposing ratio
R^{max}_{dpi}	maximum capacity of product p of recovery center i
R^{min}_{dpi}	minimum capacity of product p of recovery center i
Rm_{duql}	repairing ratio for the second customers
RRe_{duql}	recycling ratio
rrp_{ip}	revenues due to the return of remanufacturable product p to plant i
rrs_{ip}	revenues due to the return of recycled product p to supplier i
$rsfm_{ip}$	revenues on the sale of final product p to first market i
$rssm_{ip}$	revenues on the sale of final product p to second market i
S^{max}_{pi}	maximum supply capacity of product p of each supplier i
S^{min}_{pi}	minimum supply capacity of product p of each supplier i
$w_{dpp'}$	utilization factor of raw material p used for manufacturing product p' considering a product design d
αp	confidence level of profit
αr	confidence level of revenues
β	weighted factor, which is a trade-off coefficient to change the relative importance of the risk term with respect to the expected values of revenues and costs
δ^P_{ri}	unit cost of consumption of manufacturing resource r at entity i
λ_{pir}	amount of manufacturing resource r required to produce a unit of product p at plant i
$\varphi_{dpp'}$	conversion factor of products p to recycled material p' in design d

Continuous variables

$CVaRp$	level of risk that exists below a given value of profit
$CVaRrsp$	level of risk that exists below a given value of revenues obtained by returning materials into the forward network
$dv\eta p_s$	deviational variable of scenario s that quantifies the reduction of profit of the scenario s when its profit are less than ηp
$dv\eta r_s$	deviational variable of scenario s that quantifies the reduction of revenues of the scenario s when its revenues are less than ηr
in_{iptn}	inventory level of material p being held in factory or distribution center i during time period t at node n
OC_s	operational cost of scenario s
p_{diptn}	rate of production of product p considering the product design d at entity i during time period t at node n
q_{ijptn}	rate of flow of material p transferred from entity i to entity j during time period t at node n
R_s	revenues of scenario s
RSP_s	revenues of scenario s considering all products transported from recycling centers to suppliers and factories
νC^P_i	cost of establishing plant i
νC^R_i	cost of establishing recovery center i
νC^{Re}_i	cost of establishing recycling center i
ηp	level of expected profit
ηr	level of expected revenues

Binary variables

yd_d	1 if product design d is selected, 0 otherwise
y_i	1 if entity i belongs to the network, 0 otherwise

Appendix B

Table B1
Demand for each product from each first market (DEC_{pit}) [ton/trimester].

Period	Product	UK	ES	IT	FR	SE	IE	NL	GR	DK	FI	PT	BE	CH	NO	AT	DE	PL	TR
t1	p1	322	308	295	293	280	268	264	252	241	598	572	547	544	520	497	490	468	447
	p2	334	319	305	304	290	277	273	261	250	426	407	389	387	370	354	348	333	319
	p3	368	352	337	335	320	306	301	288	276	518	495	473	471	450	430	424	405	387
	p4	380	363	347	345	330	316	311	297	284	506	484	463	460	440	421	414	396	379
	p5	322	308	295	293	280	268	264	252	241	495	473	452	450	430	411	405	387	370
	p6	219	209	200	199	190	182	179	171	164	403	385	368	366	350	335	330	315	301
	p7	253	242	232	230	220	211	207	198	190	575	550	526	523	500	478	471	450	430
	p8	368	352	337	335	320	306	301	288	276	690	660	631	627	600	573	565	540	516
	p9	207	198	190	189	180	172	170	162	155	449	429	410	408	390	373	367	351	336
	p10	219	209	200	199	190	182	179	171	164	414	396	379	377	360	344	339	324	310
t2	p1	322	328	268	264	252	241	598	565	540	516	241	598	572	547	544	520	497	490
	p2	334	319	302	304	240	277	273	271	240	426	407	389	387	270	254	228	397	319
	p3	368	352	180	172	170	162	155	429	429	410	276	518	495	473	471	450	430	424
	p4	380	363	347	345	330	316	311	297	284	506	484	463	460	440	421	414	396	379
	p5	322	308	295	293	280	268	264	252	241	495	473	452	450	252	241	405	387	370
	p6	119	369	379	199	190	182	179	171	164	403	385	368	366	350	335	330	315	301
	p7	253	242	232	230	220	211	207	198	190	252	241	526	523	300	378	481	450	430
	p8	368	352	337	335	360	306	301	288	276	690	660	631	627	450	273	565	540	516
	p9	207	198	190	189	170	172	170	162	155	449	429	335	320	306	301	288	276	305
	p10	219	209	200	199	290	79	171	164	414	396	379	377	379	377	360	344	339	324
t3	p1	410	408	390	373	367	190	182	179	171	540	516	241	598	572	547	544	520	447
	p2	334	319	302	304	240	277	273	271	240	426	407	389	387	270	254	228	397	319
	p3	368	352	180	172	170	162	155	449	429	410	276	518	495	273	471	450	430	424
	p4	350	373	347	345	330	316	311	297	284	506	484	463	460	240	421	514	336	379
	p5	322	228	295	293	280	268	264	252	241	495	473	452	450	252	241	405	387	370
	p6	119	396	379	199	190	163	170	141	164	403	385	89	170	172	170	162	315	301
	p7	253	242	232	306	301	288	276	495	198	190	252	241	526	523	300	378	481	450
	p8	368	352	337	335	360	306	301	288	276	690	660	631	627	450	273	565	140	516
	p9	207	298	190	189	170	172	170	162	155	449	429	335	320	306	301	28	276	305
	p10	219	239	200	199	290	241	598	572	547	414	396	379	377	379	377	360	344	339

Table B2
Demand for each product from each second market ($DECC_{pit}$) [ton/trimester].

Period	Product	Second Markets				
		UK	IT	FR	BE	NO
t1	p1	54	0	0	52	0
	p2	0	0	124	120	79
	p3	0	73	40	100	44
	p4	84	0	212	0	162
	p5	78	24	24	76	24
	p6	24	24	148	144	103
	p7	24	97	64	124	68
	p8	108	24	236	24	186
	p9	70	16	16	136	16
	p10	24	24	148	144	103
t2	p1	134	64	144	52	40
	p2	32	58	124	120	79
	p3	44	73	40	100	124
	p4	140	96	212	0	162
	p5	78	24	84	76	24
	p6	52	24	148	144	103
	p7	79	97	64	124	68
	p8	108	24	236	24	186
	p9	70	16	96	136	16
	p10	72	24	105	96	103
t3	p1	40	64	168	52	40
	p2	112	58	124	120	79
	p3	44	153	40	100	124
	p4	140	70	84	16	162
	p5	78	24	84	76	24
	p6	52	38	148	144	103
	p7	79	97	64	124	68
	p8	108	104	236	24	44
	p9	70	16	96	136	16
	p10	152	24	105	96	103

Table B3
Revenues on the sale of final product p to second market i ($rssm_{ip}$) [rmu].

Product	UK	NO	FR	BE	IT
p1	8.08	7.5	8.78	6.3	7.5
p2	8.64	6.06	9.23	7.56	6.06
p3	9.64	3.87	8.28	7.84	3.87
p4	8.08	4.1	6.69	6.3	4.1
p5	7.25	4.15	6.24	5.45	4.15
p6	8.64	6.06	9.23	7.56	6.06
p7	9.64	3.87	8.28	7.84	3.87
p8	9.64	3.87	8.28	7.84	3.87
p9	8.64	6.06	9.23	7.56	6.06
p10	8.08	7.5	8.78	6.3	7.5

Table B4
Revenues due to the return of recycled product p to supplier i (rss_{ip}) [rmu].

Product	Suppliers				
	RU	UA	TR	BG	RO
rm1	0.64	0.51	0.7	0.53	0.51
rm2	0.7	0.37	0.67	0.58	0.37
rm3	0.68	0.3	0.57	0.54	0.3
rm4	0.58	0.3	0.49	0.44	0.3

Table B5
Revenues on the sale of final product p to first market i ($rsfm_{ip}$) [rmu].

Product	First Market																	
	UK	ES	IT	FR	SE	IE	NL	GR	DK	FI	PT	BE	CH	NO	AT	DE	PL	TR
p1	11.55	10.72	10.72	12.56	7.34	9	8.89	10.72	8.06	6.04	15.87	9	9.43	10.72	7.66	13.14	10.94	12.49
p2	12.34	8.67	8.67	13.21	9.97	10.8	9.72	8.67	8.89	8.06	16.7	10.8	10.11	8.67	7.99	13.78	11.01	13.32
p3	13.78	5.54	5.54	11.84	12.2	11.23	11.44	5.54	11.08	11.44	15.8	11.23	9.54	5.54	7.95	12.2	7.81	14.72
p4	11.55	5.86	5.86	9.57	9.57	9	9.18	5.86	8.82	11.77	13.57	9	7.3	5.86	5.68	9.97	7.41	12.49
p5	10.36	5.94	5.94	8.92	8.74	7.81	7.99	5.94	7.63	9.18	12.88	7.81	6.55	5.94	6.3	9.28	6.76	11.3
p6	12.34	8.67	8.67	13.21	9.97	10.8	9.72	8.67	8.89	8.06	16.7	10.8	10.11	8.67	7.99	13.78	11.01	13.32
p7	13.78	5.54	5.54	11.84	12.2	11.23	11.44	5.54	11.08	11.44	15.8	11.23	9.54	5.54	7.95	12.2	7.81	14.72
p8	13.78	5.54	5.54	11.84	12.2	11.23	11.44	5.54	11.08	11.44	15.8	11.23	9.54	5.54	7.95	12.2	7.81	14.72
p9	12.34	8.67	8.67	13.21	9.97	10.8	9.72	8.67	8.89	8.06	16.7	10.8	10.11	8.67	7.99	13.78	11.01	13.32
p10	11.55	10.72	10.72	12.56	7.34	9	8.89	10.72	8.06	6.04	15.87	9	9.43	10.72	7.66	13.14	10.94	12.49

Table B6
Revenues due to the return of remanufacturable product p to plant i (rrp_{ip}) [rmu].

Product	Plants														
	UK	ES	IT	FR	SE	IE	NL	GR	DK	FI	PT	BE	CH	NO	AT
p1	0.79	0.64	0.64	0.85	0.57	0.66	0.62	0.64	0.56	0.46	1.08	0.66	0.64	0.64	0.52
p2	0.86	0.47	0.47	0.83	0.73	0.73	0.7	0.47	0.66	0.64	1.08	0.73	0.65	0.47	0.52
p3	0.84	0.38	0.38	0.71	0.72	0.67	0.68	0.38	0.66	0.77	0.97	0.67	0.56	0.38	0.45
p4	0.72	0.39	0.39	0.61	0.6	0.56	0.56	0.39	0.54	0.69	0.88	0.56	0.46	0.39	0.39
p5	0.75	0.48	0.48	0.73	0.62	0.62	0.58	0.48	0.54	0.57	0.98	0.62	0.55	0.48	0.47
p6	0.86	0.47	0.47	0.83	0.73	0.73	0.7	0.47	0.66	0.64	1.08	0.73	0.65	0.47	0.52
p7	0.91	0.36	0.36	0.78	0.81	0.74	0.76	0.36	0.73	0.76	1.05	0.74	0.63	0.36	0.52
p8	0.86	0.47	0.47	0.83	0.73	0.73	0.7	0.47	0.66	0.64	1.08	0.73	0.65	0.47	0.52
p9	0.79	0.64	0.64	0.85	0.57	0.66	0.62	0.64	0.56	0.46	1.08	0.66	0.64	0.64	0.52
p10	0.76	0.71	0.71	0.83	0.48	0.6	0.59	0.71	0.53	0.4	1.05	0.6	0.62	0.71	0.5

Table B7
Unit handling cost of each material at Plants, Distribution Centers and Recovery Centers (C_{pi}^{DH} andC_{pi}^{DRH}) [rmu].

Products	Plants/Distribution Centers/Recovery Centers														
	UK	ES	IT	FR	SE	IE	NL	GR	DK	FI	PT	BE	CH	NO	AT
p1-p10	0.56	0.64	0.49	0.48	0.46	0.72	0.51	0.77	0.5	0.71	0.28	0.16	0.07	0.74	0.71

Table B8
Amount of manufacturing resource r required to produce a unit amount of product p in each Plant i (λ_{pir}) [hour/ton].

Plants	Products	Resources					
		r1	r2	r3	r4	r5	r6
UK, IT, SE, NL, DK, PT, CH, AT	p1-p4	0.038	0.007	0.056	0.021	0.032	0.026
	p5-p7	0.033	0.023	0.028	0.035	0.033	0.023
	p8-p10	0.012	0.065	0.087	0.045	0.036	0.039
ES, FR, IE, GR, FI, BE, NO	p1-p4	0.045	0.033	0.026	0.04	0.022	0.04
	p5-p7	0.045	0.032	0.056	0.04	0.022	0.04
	p8-p10	0.012	0.065	0.087	0.045	0.036	0.039

Table B9
Unit cost of consumption of manufacturing resource r in each Plant i (δ^{P}_{ri}) [rmu/hour].

Resource	Plants														
	UK	ES	IT	FR	SE	IE	NL	GR	DK	FI	PT	BE	CH	NO	AT
r1	4.4	10.4	12.4	10.6	7.2	11.6	7.4	12.4	9.6	8.2	12.2	5.6	7	10.4	9.6
r2	4.8	4.6	4.4	10.8	8.2	10.2	11.6	6.2	9.6	8.2	10.4	5.6	8.6	7.6	14.4
r3	11	7.2	6.6	6.4	11	8.2	10.4	11.6	9.6	11.2	12.8	5.6	8.8	7.6	7.2
r4	4.6	2.6	6.6	5	10.8	6.4	8.8	8.2	11	6.8	7	3	9.4	10.4	9.8
r5	7	5.2	6.6	6.6	8.6	8.6	5.8	7.2	13.2	9.4	6.6	5	7.6	9.2	10.4
r6	10.6	10.6	8.6	10.8	6.2	6.2	8.2	10.4	9.4	11.6	6.6	7	4.6	7	9.6

Table B10
Unit transportation cost of material from recycling centers to Suppliers (C^{T}_{pij}) [rmu/ton].

Recycling centers	Suppliers				
	RU	UA	TR	BG	RO
FR	1.01	1.07	2.1	1.52	0.95
DE	2.27	1.77	0.78	1.18	1.07
IT	1.18	1.9	1.28	0.9	1.43

Table B11
Unit transportation cost of material from each Recovery center to each Disposal Site or Recycling Center (C^{T}_{pij}) [rmu/ton].

Recovery Centers	Disposal Sites/Recycling Centers		
	FR	DE	IT
UK	0.65	0.2	0.98
ES	1.68	1.46	1.23
IT	1.52	1.77	1.3
FR	1.52	1.18	0.9
SE	0.26	1.51	0.9
IE	1.48	0.25	0.86
NL	0.66	0.65	0.04
GR	2.22	2.82	2.3
DK	0.04	1.27	0.66
FI	0.9	2.17	1.56
PT	2.24	1.9	1.62
BE	0.7	0.57	0.08
CH	0.95	1.07	0.63
NO	0.48	2.58	1.04
AT	0.9	1.41	0.79

Table B12
Unit transportation cost of material from First Markets to Recovery Centers (C^T_{pij}) [rmu/ton].

First Market	Recovery Centers														
	UK	ES	IT	FR	SE	IE	NL	GR	DK	FI	PT	BE	CH	NO	AT
UK	0.2	1.46	1.77	1.18	1.51	0.25	0.65	2.82	1.27	2.17	1.9	0.57	1.07	1.65	1.31
ES	1.46	0.2	1.09	0.32	1.93	1.67	1.23	2.47	1.68	2.58	0.93	1.1	0.85	2.06	1.31
IT	1.77	1.09	0.2	1.01	1.77	1.97	1.3	1	1.52	2.44	1.89	1.22	0.69	2	0.86
FR	1.18	0.32	1.01	0.2	1.76	1.38	0.9	2.39	1.52	2.42	0.9	0.82	0.77	1.9	1.23
SE	1.51	1.93	1.77	1.76	0.28	1.72	0.9	2.47	0.26	0.76	2.48	0.94	1.2	0.23	1.14
IE	0.25	1.67	1.97	1.38	1.72	0.04	0.86	3.03	1.48	2.38	2.1	0.78	1.28	1.86	1.53
NL	0.65	1.23	1.3	0.9	0.9	0.86	0.04	2.3	0.66	1.56	1.62	0.08	0.63	1.04	0.79
GR	2.82	2.47	1	2.39	2.47	3.03	2.3	0.04	2.22	2.88	3.27	2.22	1.89	2.7	1.53
DK	1.27	1.68	1.52	1.52	0.26	1.48	0.66	2.22	0.04	0.9	2.24	0.7	0.95	0.48	0.9
FI	2.17	2.58	2.44	2.42	0.76	2.38	1.56	2.88	0.9	0.24	3.14	1.6	2.09	0.76	1.7
PT	1.9	0.93	1.89	0.9	2.48	2.1	1.62	3.27	2.24	3.14	0.08	1.54	1.58	2.62	2.12
BE	0.57	1.1	1.22	0.82	0.94	0.78	0.88	2.22	0.7	1.6	1.54	0.04	0.6	1.09	0.75
CH	1.07	0.85	0.69	0.77	1.2	1.28	0.63	1.89	0.95	2.09	1.58	0.6	0.12	1.34	0.47
NO	1.65	2.06	2	1.9	0.23	1.86	1.04	2.7	0.48	0.78	2.62	1.09	1.34	0.28	1.38
AT	1.31	1.31	0.86	1.23	1.14	1.53	0.79	1.53	0.9	1.7	2.12	0.75	0.47	1.38	0.08
DE	0.75	1.16	1.17	0.99	0.78	0.96	0.2	2.08	0.54	1.43	1.72	0.18	0.5	0.92	0.62
PL	1.58	1.93	1.44	1.81	1.05	1.78	0.98	1.88	0.8	0.98	2.54	1.01	1.1	1.28	0.7
TR	2.7	2.36	1.38	2.27	2.35	2.92	2.18	0.88	2.1	2.76	3.16	2.14	1.76	2.58	1.41

Table B13
Unit transportation cost of material from Redistribution Centers to Second Markets (C^T_{pij}) [rmu/ton].

Redistribution centers	Second Markets				
	UK	NO	FR	BE	IT
UK	0.97	1.1	0.2	1.53	1.65
ES	1.93	2.36	1.09	2.36	1.46
IT	1.44	1.38	0.2	1.38	1.77
FR	1.81	2.27	1.01	2.27	1.18
SE	1.05	2.35	1.77	2.35	1.51
IE	1.78	1.32	1.97	2.92	0.25
NL	0.98	2.18	1.3	2.18	0.65
GR	1.88	0.88	1	0.88	2.82
DK	0.8	2.1	1.52	2.1	1.27
FI	0.98	1.96	2.44	2.76	2.17
PT	1.74	2.36	1.89	3.16	1.9
BE	1.01	2.14	1.22	2.14	0.57
CH	1.1	1.76	0.69	1.76	1.07
NO	1.28	1.78	2	2.58	1.65
AT	0.7	1.41	0.86	1.41	1.31

Table B14
Unit transportation cost of material from Suppliers to Plants (C^T_{pij}) [rmu/ton].

Supplier	Plants														
	UK	ES	IT	FR	SE	IE	NL	GR	DK	FI	PT	BE	CH	NO	AT
RU	2.57	2.92	2.43	2.79	1.63	2.78	1.98	2.38	1.79	0.94	3.53	2	2.1	1.66	1.7
UA	2.74	3.06	2.45	2.94	2.22	2.96	2.16	1.93	1.98	1.79	3.71	2.4	2.25	2.45	1.78
TR	3.06	2.71	1.74	2.63	2.71	3.27	2.54	1.23	2.46	2.54	3.51	2.5	2.12	2.94	1.77
BG	2.57	2.22	1.65	2.13	2.13	2.78	2.04	0.9	1.96	2.62	3.02	2	1.62	2.44	1.26
RO	2.3	2.06	1.5	1.98	1.94	2.51	1.78	0.92	1.7	2.04	2.86	1.74	1.46	2.18	1

Table B15
Unit transportation cost of material from Plants/Recovery Centers to Distribution Centers/Redistribution Centers (C^T_{pij}) [rmu/ton].

Origen Entity	Destination Entities														
	UK	ES	IT	FR	SE	IE	NL	GR	DK	FI	PT	BE	CH	NO	AT
UK		1.46	1.77	1.18	1.51	0.25	0.65	2.82	1.27	2.17	1.9	0.57	1.07	1.65	1.31
ES	1.46		1.09	0.32	1.93	1.67	1.23	2.47	1.68	2.58	0.93	1.1	0.85	2.06	1.31
IT	1.77	1.09		1.01	1.77	1.97	1.3	1	1.52	2.44	1.89	1.22	0.69	2	0.86
FR	1.18	0.32	1.01		1.76	1.38	0.9	2.39	1.52	2.42	0.9	0.82	0.77	1.9	1.23
SE	1.51	1.93	1.77	1.76		1.72	0.9	2.47	0.26	0.76	2.48	0.94	1.2	0.23	1.14
IE	0.25	1.67	1.97	1.38	1.72		0.86	3.03	1.48	2.38	2.1	0.78	1.28	1.86	1.53
NL	0.65	1.23	1.3	0.9	0.9	0.86		2.3	0.66	1.56	1.62	0.08	0.63	1.04	0.79
GR	2.82	2.47	1	2.39	2.47	3.03	2.3		2.22	2.88	3.27	2.22	1.89	2.7	1.53
DK	1.27	1.68	1.52	1.52	0.26	1.48	0.66	2.22		0.9	2.24	0.7	0.95	0.48	0.9
FI	2.17	2.58	2.44	2.42	0.76	2.38	1.56	2.88	0.9		3.14	1.6	2.09	0.78	1.7
PT	1.9	0.93	1.89	0.9	2.48	2.1	1.62	3.27	2.24	3.14		1.54	1.58	2.62	2.12
BE	0.57	1.1	1.22	0.82	0.94	0.78	0.08	2.22	0.7	1.6	1.54		0.6	1.09	0.75
CH	1.07	0.85	0.69	0.77	1.2	1.28	0.63	1.89	0.95	2.09	1.58	0.6		1.34	0.47
NO	1.65	2.06	2	1.9	0.23	1.86	1.04	2.7	0.48	0.78	2.62	1.09	1.34		1.38
AT	1.31	1.31	0.86	1.23	1.14	1.53	0.79	1.53	0.9	1.7	2.12	0.75	0.47	1.38	

Table B16
Unit transportation cost of material from Distribution Centers to First Markets (C^T_{pij}) [rmu/ton].

Distribution Center	First Markets																	
	UK	ES	IT	FR	SE	IE	NL	GR	DK	FI	PT	BE	CH	NO	AT	DE	PL	TR
UK	0.2	1.46	1.77	1.18	1.51	0.25	0.65	2.82	1.27	2.17	1.9	0.57	1.07	1.65	1.31	0.75	1.58	2.7
ES	1.46	0.2	1.09	0.32	1.93	1.67	1.23	2.47	1.68	2.58	0.93	1.1	0.85	2.06	1.31	1.16	1.93	2.36
IT	1.77	1.09	0.2	1.01	1.77	1.97	1.3	1	1.52	2.44	1.89	1.22	0.69	2	0.86	1.17	1.44	1.38
FR	1.18	0.32	1.01	0.2	1.76	1.38	0.9	2.39	1.52	2.42	0.9	0.82	0.77	1.9	1.23	0.99	1.81	2.27
SE	1.51	1.93	1.77	1.76	0.28	1.72	0.9	2.47	0.26	0.76	2.48	0.94	1.2	0.23	1.14	0.78	1.05	2.35
IE	0.25	1.67	1.97	1.38	1.72	0.04	0.86	3.03	1.48	2.38	2.1	0.78	1.28	1.86	1.53	0.96	1.78	2.92
NL	0.65	1.23	1.3	0.9	0.9	0.86	0.04	2.3	0.66	1.56	1.62	0.88	0.63	1.04	0.79	0.2	0.98	2.18
GR	2.82	2.47	1	2.39	2.47	3.03	2.3	0.04	2.22	2.88	3.27	2.22	1.89	2.7	1.53	2.08	1.88	0.88
DK	1.27	1.68	1.52	1.52	0.26	1.48	0.66	2.22	0.04	0.9	2.24	0.7	0.95	0.48	0.9	0.54	0.8	2.1
FI	2.17	2.58	2.44	2.42	0.76	2.38	1.56	2.88	0.9	0.24	3.14	1.6	2.09	0.78	1.7	1.43	0.98	2.76
PT	1.9	0.93	1.89	0.9	2.48	2.1	1.62	3.27	2.24	3.14	0.08	1.54	1.58	2.62	2.12	1.72	2.54	3.16
BE	0.57	1.1	1.22	0.82	0.94	0.78	0.08	2.22	0.7	1.6	1.54	0.04	0.6	1.09	0.75	0.18	1.01	2.14
CH	1.07	0.85	0.69	0.77	1.2	1.28	0.63	1.89	0.95	2.09	1.58	0.6	0.12	1.34	0.47	0.5	1.1	1.76
NO	1.65	2.06	2	1.9	0.23	1.86	1.04	2.7	0.48	0.76	2.62	1.09	1.34	0.28	1.38	0.92	1.28	2.58
AT	1.31	1.31	0.86	1.23	1.14	1.53	0.79	1.53	0.9	1.7	2.12	0.75	0.47	1.38	0.08	0.62	0.7	1.41

Table B17
Unit Fixed cost for establishing distribution centers for the planning horizon of 3 years [rmu].

Distribution Center	Fixed Cost
UK	120,000
ES	45,000
IT	30,000
FR	60,000
SE	67,500
IE	30,000
NL	60,000
GR	30,000
DK	45,000
FI	15,000
PT	37,500
BE	75,000
CH	105,000
NO	52,500
AT	97,500

Table B18
Unit Fixed cost for establishing plants for the planning horizon of 3 years [rmu].

Plant	Product Designs		
	d_1	d_2	d_3
UK	400,000	410,000	420,000
ES	150,000	160,000	170,000
IT	100,000	110,000	120,000
FR	200,000	210,000	220,000
SE	225,000	235,000	245,000
IE	100,000	110,000	120,000
NL	200,000	210,000	220,000
GR	100,000	110,000	120,000
DK	150,000	160,000	170,000
FI	50,000	60,000	70,000
PT	125,000	135,000	145,000
BE	250,000	260,000	270,000
CH	350,000	360,000	370,000
NO	175,000	185,000	195,000
AT	325,000	335,000	345,000

Table B19
Unit Fixed cost for establishing Recovery Centers for the planning horizon of 3 years [rmu].

Recovery Centers	Product Designs		
	d_1	d_2	d_3
UK	18,000	25,500	30,000
ES	21,000	29,750	35,000
IT	21,000	29,750	35,000
FR	6000	8500	10,000
SE	7500	10,625	12,500
IE	3000	4250	5000
NL	16,800	23,800	28,000
GR	6000	8500	10,000
DK	9000	12,750	15,000
FI	12,000	17,000	20,000
PT	6900	9775	11,500
BE	3000	4250	5000
CH	4200	5950	7000
NO	10,500	14,875	17,500
AT	20,700	29,325	34,500

Table B20
Unit Fixed cost for establishing Recycling Centers for the planning horizon of 3 years [rmu].

Recycling Centers	Product Designs		
	d_1	d_2	d_3
IT	4800	6800	8000
FR	4200	5950	7000
DE	6000	8500	10000

Table B21
Unit Fixed cost for establishing Redistribution Centers for the planning horizon of 3 years [rmu].

Redistribution Center	Fixed Cost
UK	30,000
ES	35,000
IT	35,000
FR	10,000
SE	12,500
IE	5000
NL	28,000
GR	10,000
DK	15,000
FI	20,000
PT	11,500
BE	5000
CH	7000
NO	17,500
AT	34,500

Table B22
Unit Fixed cost for establishing Disposal sites for the planning horizon of 3 years [rmu].

Disposal Site	Fixed Cost
IT	5000
FR	6000
DE	8000

Table B23
Maximum and minimum rate of availability of raw materials (S_{pi}^{max}, S_{pi}^{min}) [tons//trimester] and fixed cost of establishing relationship with suppliers (C_i^S) [rmu].

Suppliers	Minimum rate	Maximum rate	C_i^S
RU,UA,TR,BG,RO	100	5000	30,000

Table B24
Unit purchasing price of raw materials [rmu/ton].

Suppliers	Product	Purchasing Price
RU,UA,TR,BG,RO	rm1	1.21
	rm2	1.1
	rm3	1.04
	rm4	1.29

Table B25
Quality and quantity levels for the returned products.

Discrete Event Return Quality	Prob.	Discrete Event Return Quantity	Prob.
eqt1	0.25	eql1	0.2
eqt2	0.35	eql2	0.45
eqt3	0.40	eql3	0.35

Table B26
Utilization factor ($w_{dpp'}$) of raw material p used for final product p'.

Raw Material	Product Design	Final Products									
		p5	p6	p7	p8	p9	p10	p11	p12	p13	p14
rm1	d1	0.15	0.22	0.28	0.33	0.46	0.22	0.3	0.33	0.28	0.33
	d2	0.15	0.22	0.28	0.33	0.46	0.22	0.3	0.33	0.28	0.33
	d3	0.35	0.1	0.38	0.1	0.25	0.23	0.15	0.17	0.3	0.17
rm2	d1	0.35	0.1	0.38	0.1	0.25	0.23	0.15	0.17	0.3	0.17
	d2	0.15	0.45	0.18	0.33	0.15	0.45	0.4	0.33	0.28	0.33
	d3	0.35	0.23	0.16	0.24	0.14	0.1	0.15	0.17	0.14	0.17
rm3	d1	0.35	0.23	0.16	0.24	0.14	0.1	0.15	0.17	0.14	0.17
	d2	0.35	0.1	0.38	0.1	0.25	0.23	0.15	0.17	0.3	0.17
	d3	0.15	0.22	0.28	0.33	0.46	0.22	0.3	0.33	0.28	0.33
rm4	d1	0.15	0.45	0.18	0.33	0.15	0.45	0.4	0.33	0.28	0.33
	d2	0.35	0.23	0.16	0.24	0.14	0.1	0.15	0.17	0.14	0.17
	d3	0.15	0.45	0.18	0.33	0.15	0.45	0.4	0.33	0.28	0.33

Table B27
Unit inventory cost for material p in case of established production capability/redistribution capability at a node during time period t (C^{IP}_{pit}, C^{IDR}_{pit}) [rmu/ton].

Product	Plants/Redistribution Centers														
	UK	ES	IT	FR	SE	IE	NL	GR	DK	FI	PT	BE	CH	NO	AT
p1	4.25	4.55	4.98	4.95	4.55	4.98	3	3.22	4.23	3.21	2.72	1.23	3	2.22	4.23
p2	3.25	3.55	4.72	3	2.22	4.23	4.98	4.25	4.55	4.08	3	3.22	4.23	4.98	4.25
p3	4	2.85	3.06	4.4	2.85	2.06	4.25	4.25	4.98	4	2.85	3	3.21	3.72	4.23
p4	3	2.22	4.23	3.21	2.72	4.23	2.22	4.23	4.98	4.25	4.55	4.98	4.98	3	2.22
p5	4.25	4.55	4.08	4	3.85	3.06	4.4	2.85	2.06	4.98	3	2.22	4.23	3.21	3.72
p6	3.25	3.5	4.92	3	3.22	3.23	3.21	2.72	4.23	2.22	4.23	4.98	4.25	4.55	4.98
p7	4.3	4.85	3.06	4.55	4.98	4	2.85	3.06	4.4	2.85	2.06	3	2.22	4.23	2.85
p8	3	3.22	4.73	4.4	2.85	2.06	4.98	3.56	4.4	2.85	2.06	2.85	2.06	4.25	4.55
p9	4.4	2.85	3.06	4.85	3.06	2.55	4.98	4	3.85	4.06	4.4	3.85	2.06	2.06	3
p10	3.21	2.72	4.23	2.72	4.98	4.98	3	2.22	4.98	4.25	4.55	4.98	3.06	4.4	2.85

Notes for Tables B26 and B27:
Rm1 and rm4 are considered critical raw materials in the manufacture of the final products and, therefore, their recovery is highly desirable. The characteristics of the different designs are analyzed considering the previously mentioned context.
As it can be seen in Table B26, rm1 and rm4 in design d1 have, on average, great importance in the manufacture of final products. As it can be seen in Table B27, design d1 allows, on average, a significant recovery of raw materials rm1, rm3 and rm4. However, the raw materials with the highest incidence in the manufacture of final products for design d1 are rm1 and rm4. In Table B27, it can also be seen that the recovery levels of the raw materials rm1 and rm4 are high in half the problems and low or zero in the other half. The raw materials rm1 and rm4 are not recovered for the final products p4, p7, p8 and p9, as well as p3, p7, p8 and p10, respectively.
On the other hand, as it can be seen in Table B26, when the design d2 is considered, raw materials rm1 and rm2 have, on average, great importance in the manufacture of final products. As it can be observed in Table B27, the design d2 allows, on average, an important recovery of the raw materials rm1, rm3 and rm4. However, the only raw material with a high incidence in the manufacture of the final products is the rm1.
Finally, as it can be seen in Table B26, the design d3 requires, on average, more raw materials rm3 and rm4 than rm1 and rm2 for the manufacture of the final products. As it can be observed in Table B27, the design d3 allows, on average, a greater recovery of the raw material rm1, which is not a raw material with a high incidence in the manufacture of final products. In addition, the design d3 allows to recover the raw material rm4 only in 4 cases (p1, p2, p5 and p9) with the recovery being very poor for product p9.

Table B28
Conversion factor $\varphi_{dpp'}$ of products p to recycled raw material p‘ in design d.

Final Product	Product Design	Recycled raw materials			
		rm1	rm2	rm3	rm4
	d1	0.52	0.012	0.012	0.38
p1	d2	0.56	0.032	0.032	0.43
	d3	0.6	0.052	0	0.38
	d1	0.51	0.038	0.41	0.33
p2	d2	0.55	0.058	0.43	0.38
	d3	0.59	0.078	0	0.33
	d1	0.21	0	0.26	0
p3	d2	0.25	0.005	0.28	0
	d3	0.29	0.025	0.24	0
	d1	0	0.11	0.04	0.09
p4	d2	0.025	0.13	0.06	0.14
	d3	0.065	0.15	0	0
	d1	0.26	0.01	0.26	0.31
p5	d2	0.3	0.03	0.28	0.36
	d3	0.34	0.05	0.24	0.31
	d1	0.09	0.03	0	0.15
p6	d2	0.13	0.05	0.007	0.2
	d3	0.17	0.07	0	0
	d1	0	0.04	0.12	0
p7	d2	0.003	0.06	0.14	0.04
	d3	0.043	0.08	0	0
	d1	0	0.13	0.11	0
p8	d2	0	0.15	0.13	0.005
	d3	0.04	0.17	0.09	0
	d1	0	0.11	0.04	0.09
p9	d2	0.025	0.13	0.06	0.14
	d3	0.065	0.15	0.02	0.09
	d1	0.52	0.012	0.3	0
p10	d2	0.56	0.032	0.32	0.043
	d3	0.6	0.052	0.28	0

Table B29
Emission costs [rmu].

	Emission cost
Forward network (ecf)	0.344
Reverse network (ecr)	0.344

Table B30
Unit recovering, remanufacturing and repairing cost for recoverable product p (C_{pi}^{RV}), for remanufacturable product p (C_{pi}^{RM}) and for repairable product p (C_{pi}^{RP}) in Recovery Centers [rmu/ton].

Product	Recovery Centers														
	UK	ES	IT	FR	SE	IE	NL	GR	DK	FI	PT	BE	CH	NO	AT
p1	0.64	0.68	0.66	0.64	0.68	0.46	0.16	0.24	0.2	0.33	0.29	0.21	0.64	0.62	0.16
p2	0.58	0.64	0.62	0.16	0.44	0.2	0.36	0.39	0.51	0.36	0.29	0.11	0.26	0.44	0.2
p3	0.16	0.24	0.2	0.36	0.29	0.51	0.67	0.26	0.44	0.2	0.36	0.39	0.51	0.36	0.59
p4	0.36	0.29	0.31	0.36	0.29	0.11	0.51	0.67	0.26	0.44	0.2	0.36	0.39	0.58	0.21
p5	0.64	0.68	0.66	0.64	0.68	0.46	0.16	0.24	0.2	0.33	0.29	0.21	0.64	0.62	0.16
p6	0.58	0.64	0.62	0.16	0.44	0.2	0.36	0.39	0.51	0.36	0.29	0.11	0.26	0.44	0.2
p7	0.16	0.24	0.2	0.36	0.29	0.51	0.67	0.26	0.44	0.2	0.36	0.39	0.51	0.36	0.59
p8	0.36	0.29	0.31	0.16	0.29	0.31	0.51	0.67	0.26	0.44	0.2	0.36	0.39	0.58	0.31
p9	0.46	0.24	0.2	0.66	0.29	0.51	0.67	0.26	0.44	0.2	0.36	0.39	0.51	0.36	0.59
p10	0.36	0.29	0.31	0.36	0.29	0.11	0.51	0.67	0.26	0.44	0.2	0.36	0.39	0.58	0.11

Table B31
Unit disposal cost for disposable product p in disposal site i (C_{pi}^{Di}) [rmu/ton].

Product	Disposal sites		
	FR	DE	IT
p1	0.99	0.88	1.08
p2	1.08	0.99	0.86
p3	1.64	1.23	0.89
p4	0.86	1.02	1.32
p5	0.99	0.78	1.08
p6	1.08	0.85	0.86
p7	1.64	1.23	0.89
p8	0.86	1.12	1.32
p9	1.64	1.23	0.89
p10	0.86	1.02	1.42

Table B32
Unit recycling cost when the final product p is processed by node i (C_{pi}^{Re}) [rmu/ton].

Product	Recycling centers		
	FR	DE	IT
p1	2.30	2.55	2.40
p2	3.66	2.36	2.69
p3	2.40	3.35	3.00
p4	2.42	2.57	3.26
p5	2.99	2.78	1.08
p6	3.08	3.85	0.86
p7	1.64	1.23	0.89
p8	2.86	2.12	1.32
p9	2.64	1.23	2.89
p10	2.86	1.02	1.42

Table B33
Maximum and Minimum capacity of distribution or redistribution of product p by Distribution Center i (D_{pi}^{max}, D_{pi}^{min}) or Redistribution Center i (DR_{pi}^{max}, DR_{pi}^{min}) [tons/trimester].

Distribution Center/Redistribution Center	Minimum capacity	Maximum capacity
UK	0	50,625
ES	0	81,000
IT	0	94,500
FR	0	94,500
SE	0	57,375
IE	0	54,000
NL	0	114,750
GR	0	50,625
DK	0	50,625
FI	0	135,000
PT	0	101,250
BE	0	114,750
CH	0	60,750
NO	0	57,375
AT	0	124,875

Table B34
Total rate of availability of each resource r in each Plant i (E_{ri}) [hours/trimester].

Resource	Plants														
	UK	ES	IT	FR	SE	IE	NL	GR	DK	FI	PT	BE	CH	NO	AT
r1	628	623	628	635	665	681	617	632	618	611	613	618	652	652	648
r2	645	633	626	641	617	611	658	631	638	661	628	678	636	638	672
r3	651	660	634	622	658	612	652	618	648	656	649	668	649	648	636
r4	631	636	639	657	642	622	644	651	658	647	652	635	675	642	649
r5	651	660	634	636	636	637	629	646	668	637	639	625	685	646	652
r6	631	636	639	642	618	615	611	632	678	618	636	625	636	635	648

Table B35
Maximum production rate of Plant i (P_{pid}^{max}) [tons/ trimester].

Product	Plants														
	UK	ES	IT	FR	SE	IE	NL	GR	DK	FI	PT	BE	CH	NO	AT
p1	2455	2410	2650	2935	2245	2488	2412	2650	2745	2895	2280	2455	2410	2650	2935
p2	2650	2935	2547	2235	2280	2455	2410	2650	2935	2568	2985	2578	2698	2578	2369
p3	2590	2280	2455	2410	2650	2935	2478	2457	2985	2578	2698	2574	2780	2455	2358
p4	2400	2770	2850	2955	2413	2657	2935	2896	2650	2935	2237	2035	2540	2455	2410
p5	2745	2895	2280	2455	2410	2650	2935	2365	2487	2400	2235	2658	2698	2923	2578
p6	2905	2595	2698	2590	2280	2455	2410	2658	2487	2422	2785	2589	2698	2968	2545
p7	2408	2778	2923	2545	2698	2500	2280	2455	2410	2487	2635	2235	2352	2635	2935
p8	2415	2870	2945	2635	2698	2512	2200	2455	2410	2445	2435	2202	2457	2698	2977
p9	2487	2425	2235	2589	2698	2590	2206	2455	2410	2787	2478	2800	2759	2634	2780
p10	2723	2898	2985	2578	2698	2578	2780	2455	2410	2977	2442	2275	2586	2128	2200

Minimum production rate of Plant i (P_{pid}^{min}) is equal to 10% of P_{pi}^{max}

Table B36
Additional parameters.

Parameter	Value
a_{dipt}	0.65
hp	3
hrd	1
$dcmf$	168

Appendix C. Computational statistics

Table C.1 shows the computational statistics for the cases solved. As it can be seen from the results in the table, Cases 5, 7, 8, 12 and 13 are computationally intensive using several hours of CPU time. Nevertheless, the time required is acceptable for making strategic decisions in a very complex problem with uncertain conditions.

Table C.1
Computational statistics.

Case	Variables		Number of Constraints	CPU [s]
	Binary	Continuous		
0	96	105,112	12,097	176
1	26	106,044	17,676	123
2	97	106,044	17,679	624
3	96	315,092	35,761	3153
4	26	423,684	69,777	13,996
5	97	423,684	69,777	20,376
6	96	315,092	35,761	11,956
7	26	423,684	69,777	292,442
8	97	423,684	69,777	324,329
9	25	953,272	156,714	29
10	25	953,272	156,714	28
11	25	953,272	156,714	31
12	97	423,684	69,777	59,804
13	97	423,684	69,777	64,391
14	25	423,684	87,219	25
15	25	423,684	87,219	28

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