Addressing the uncertain quality and quantity of returns in closed-loop supply chains

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In this work a two-stage scenario-based modeling approach is proposed in order to simultaneously deal with the design and planning decisions in supply chain networks, where both forward and reverse flows are considered (closed-loop supply chains) subject to uncertain conditions. A mixed integer linear programming (MILP) approach is developed with the underlying objective of profit maximization. Planning takes into account raw material acquisition and processing, storage and distribution of several products flowing through the network. Uncertainty is associated to the quantity and quality of the flow of products of the reverse network, which are directly affected by customers and sorting centers, respectively. The approach considers, by means of scenarios, the simultaneous integration of two important uncertainty sources, thus presenting an important modeling advantage, i.e. that of providing a better understanding of the CLSCs. The applicability of the formulation is tested with a real sized example of a Portuguese glass company.

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1. Introduction

Closed-loop supply chains (CLSC) consider, as part of the global network, not only the traditional forward flow but also the reverse flow, which is responsible for the return of products due to different reasons, ranging from non-conformity products till end-of-life products. As referred by Guide and Van Wassenhowe (2002) the companies that have been most successful with their reverse supply chains are those that closely coordinate them with the forward flow, creating the closed-loop supply chain.

In the actual context where society increased awareness towards environment is demanding a new way of looking into the supply chain structures, the efficient design and planning of CLSCs has become an important challenge for many organizations. This is mainly due to a number of reasons, such as exhaustion of natural resources, increasing environment awareness, new business opportunities and regulatory trends, among others. It is important to note that in the last few years some pieces of legislation related with environmental protection have been introduced. Among the most important regulatory policies, it should be mentioned those directives generated by the European Union, which are related to the end of life for automotive products (Directive on End-of-Life Vehicles, 2000/EC) and electrical and electronic equipment parts (Waste from Electrical and Electronic Equipment, 2003/EU). Therefore, there is no doubt that these issues have an important impact on most manufacturing organizations and on the way they operate. Thus, not only the efficient study of traditional supply chains that end at final customers and consider only the forward flow of products (FSC), is still needed, but more importantly, attention is also required for the CLSC, where the recovery of non-conform or end-of-life products is considered.

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

An analysis of relevant contributions reveals that a good number of approaches reported in the literature deal with FSC tactical decisions (Klose & Drexl, 2005; Shah, 2005). In addition, several approaches have also been proposed for the design of the reverse supply chains (for example, Gomes, Barbosa-Povo, & Novais, 2011; Gomes, Zeballos, Barbosa-Povo, & Novais, 2011; le Blanc, Fleuren, & Krikke, 2004; Realf, Ammons, & Newton, 2004), which...
confirms their importance. However, most of these approaches tend to be case dependent and hence their adaptation to other problems might prove to be hard or inappropriate.

A few works have been published considering simultaneously the forward and reverse network structures of supply chains. Some relevant and recent contributions introducing generic CLSC models include Beamon and Fernandes (2004), who developed a model for a single product CLSC design problem in order to analyze the impact of several parameters on the network structure; Lu and Bostel (2007), who proposed an approach for a remanufacturing network, composed of producers, remanufacturing sites, intermediate centers and customers; Salema, Barbosa-Póvoa, and Novais (2010), who proposed a multi-period, multi-product network model for the simultaneous design and planning of supply chains with reverse flows, where the strategic design of the SC is dealt simultaneously with the tactical decisions related to supply, production, storage and distribution. Recently, Das and Chowdhury (2012) published a closed-loop supply chain model where remanufacturing options are taken according to three pre-defined quality level of returned products. The model applicability is proven with a numerical example.

The mentioned works address only deterministic aspects of the problem. However, the non-consideration of the inherent uncertainty of the global supply chains can lead to results of inferior quality and less realistic as compared to formulations where these are explicitly accounted for (Gupta & Maranas, 2003). Most of the relevant and recent works considering the supply chain design and planning with uncertain parameters are related with forward flow (Azaron, Brown, Tarim, & Modares, 2008; Georgiadis, Tsakis, Longinis, & Sofioğlu, 2011; You & Grossmann, 2009; You, Wassick, & Grossmann, 2009). However, when the reverse supply chain is integrated within the FSC, several new sources of uncertainty appear such as returns timing, quantity and quality (Akcali & Çetinkaya, 2011). The majority of the literature related to the modeling of returns uncertainty focus on remanufacturing and inventory planning where returns quality has a considerably impact on costs. This is shown by Denizel, Ferguson, and Souza (2010) when studying the problem of uncertain returns quality in a multi-period setting. Their work focus on production planning of remanufactured products tackled through a stochastic linear programming model.

Concerning uncertainty in the design of closed-loop supply chains, few works can be found. Salema, Barbosa-Póvoa, and Novais (2007) consider the design of reverse logistics networks where capacity limits, multi-product management and uncertainty on product demands and returns quantities are accounted for in a location model. Lee, Dong, and Biau (2010) study the design of a closed-loop supply chain where decisions concerning the type of facility to be installed are taken. Three options are made available: forward or reverse processing facilities and hybrid processing facilities. Their proposed formulation, based on a warehouse location model, is extended by considering demand and returns uncertainty through a two-stage stochastic formulation. Gomes, Barbosa-Póvoa, et al. (2011) and Gomes, Zevallos, et al. (2011) study the quality of returns also through a two-stage stochastic formulation. The operations performed at sorting centers classify returns according to a discrete distribution of quality. The stochastic CLSC configuration was compared with a deterministic supply chain structure assumed as a reference case. Recently, Pishvaei and Rabban (2011) proposed a robust optimization model for the design of CLSC with uncertain demand, return and transportation costs. While considering several sources of uncertainty in the same formulation, this work focuses on a single-period problem. Baptista, Gomes, and Barbosa-Póvoa (2012) proposed a two-stage stochastic model for the design of a closed-loop supply chain model in a multi-period and multi-product context. Customers demand and returns are uncertain assuming three scenarios (pessimistic, expected and optimistic). The model is solved by the L-shape method adapted to the problem in study.

Extending the previous work developed by the authors, this work aims at filling up the void in the literature related to the design and planning of closed-loop supply chains, where different sources of returns uncertainties are considered. Not only quality is assumed to be uncertain but also quantity is assumed to follow a pre-defined probability distribution. Both sources of uncertainty are modeled simultaneously, which allows the network structure to be optimal in a complex setting of uncertainties.

This paper is structured as follows. In the next section the problem is defined. Section 3 is dedicated to the model developed for the problem, its complete formulation being provided and explained in detail. Section 4 introduces a case study to demonstrate the applicability of the approach. Numerical results are presented and discussed in Section 5. Section 6 is dedicated to the computational statistics for the instances of the case study solved. Finally, some conclusions and final remarks are presented.

2. Problem definition

This work addresses the problem of the design and planning of closed-loop supply chains where the number and location of the different types of network entities should be determined over the complete planning horizon. These entities are factories (F), warehouses (W), customers (C) and sorting centers (S). In addition, the best planning of supply, production, transportation, storage and collection must be determined for several sub-periods of the complete horizon. Thus, for the planning two time scales are required: the demand and return values must be satisfied in macro-times (for instance, yearly), while supply, production, transportation, storage and collection values must be determined in micro-times (for instance, monthly). The problem goal is the total supply chain profit maximization.

Some problem features are as follows:

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

Furthermore, returns represent an uncertain fraction of the forward products supplied, which are demand dependent with their quality being uncertain. Therefore an important part of the problem is to determine the quantity of returns available to be graded and
how much of each grade level is to be sent to factory or to proper disposal. The next section includes the assumptions adopted for addressing the uncertainty associated to quality and quantity of returns.

3. Formulation

The strategic and tactical CLSC deterministic multi-product multi-period MILP model of Salema et al. (2010) is adopted as the representative approach for the MILP formulation that is introduced in this section in order to deal with the two uncertainty sources, by means of a two-stage stochastic framework. This is one of the most general frameworks for dealing with planning problems under uncertainty (Birge & Louveaux, 1997; Gupta & Maranas, 2003; You et al., 2009). In the model proposed in this work, the uncertainty is described by a set of discrete scenarios, which denote the way it might operate during the planning horizon subject to the different quality grades and amounts of returns. Thus, a probability representing its expected occurrence is associated to each scenario.

While the two-stage scenario-based approach (TSSBA) is presented in this section, the definition of sets, variables and parameters of the model are given in Appendix A. In the proposed formulation, location variables are considered as the first-stage or design variables since these do not depend on the scenarios outcome and are to be determined before uncertain parameters are considered. Production, distribution and storage variables are modeled as the second-stage or control variables since these are the recourse variables that are to be determined in the face of uncertainty. Therefore, the uncertainty in the quality grades and amount of the return flows is translated into the operational decisions through the second-stage variables. The separation of variables in the described form is direct since the location variables are related with the design of the supply chain and these should be determined before the resolution of uncertainty in the considered parameters.

In the TSSBA the uncertainty on the amount of returns sent by customers to sorting centers is taken into account through R discrete points, each one with a given probability \( P_r \). For example, the amount of returns might be modeled with two possible levels: optimistic and pessimistic, with each level representing a given amount of return with a specific final product return fraction. While the optimistic level might be associated with return fractions of 0.60 for product \( A_1 \) and 0.50 for product \( A_2 \), the pessimistic level might be related with 0.40 and 0.30, respectively.

Furthermore, the quality of the returns sent to factory is described in terms of Q different categories, as a result of the grading process performed at the sorting centers. For example, it might be assumed that sorting centers classify the inlet returns according to three different grades: Good, Average and Bad. The quality of returns sent to factory is in turn a combination of these grades in diverse percentages, with an associated uncertainty expressed through \( G \) discrete outcomes, each one with a probability \( P_g \). For example, while outcome 1 of the sorting process might be a mix of 30\% Good, 50\% Average and 20\% Bad, outcome 2 might yield 10, 25 and 65, respectively.

The applied approach defines a scenario for each combination of the discrete points \( r \) and \( g \) (\( \Omega = \{(r,g)\} \)), and therefore, the resulting probability for each one is \( P_r P_g \), since it is assumed that both uncertainty sources are independent. For example, if two possible return levels (optimistic and pessimistic) are considered and two possible grading levels (outcomes 1 and 2) are taken into account, then the TSSBA approach will have \( 2 \times 2 = 4 \) scenarios.

The objective function of the TSSBA is to maximize the total expected supply chain profit (Eq. (1)). The performance measure is made up of (a) first stage costs, (b) expected second stage costs and (c) expected second stage revenues. It is worth noting that the costs and revenues of each scenario are affected by the probability of the scenario.

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

(b) Second stage scenario costs:
- shipment cost proportional to the amount of products transported (third term). In addition, this term also includes the cost related to the acquisition of raw material and the disposal of products,
- cost associated with the graded products that are sent to factory (fourth term). This term adds the costs of the graded products \( M_i \) of different qualities flowing from sorting centers \( I \) to factories \( F \) (represented by flow \( F_{rg} \)). The cost for each product quality category \( q \) is computed by multiplying the amount of returned products \( X_{rg} \) and the fraction of products associated with the quality \( q \) \( F_{rg} \) and the unit cost of the quality category involved \( c_{rg} \).
- penalization cost to partially satisfied demand (fifth term),
- penalization cost for any stock left in any entity except at customers (sixth term).

(c) Second stage scenario sales:
- this term includes the revenues of the final products delivered to customers (seventh term).

The model developed is described as follows:

\[
\begin{align*}
\text{Max } F &= - \sum_{i \in I} f_i Y_i - \sum_{m,i} c_{dmi} (1 - Y_i) \\
&- \sum_{(r,g) \in \Omega} P_r P_g \left( \sum_{m,i} c_{mij} X_{rgmi} + \sum_{m,i} c_{rmi} S_{rmi} X_{rgmi} \right) \\
&+ \sum_{m,i} c_{rmi} U_{rgmi} \\
&+ \sum_{m,i} c_{rmi} U_{rgmi}
\end{align*}
\]

\( (1) \)

s.t.
\[
S_{rgmi}(t,t') + \sum_{j \in F} R_{fgmi}(t') X_{rjmi}(t,t') = \sum_{j \in F} R_{fgmi}(t') X_{rjmi}(t,t') + U_{rgmi}
\]

\( (2) \)

\[
\sum_{j \in F} R_{fgmi}(t,t') X_{rjmi}(t,t') = \sum_{j \in F} R_{fgmi}(t,t') X_{rjmi}(t,t') + U_{rgmi}
\]

\( (3) \)
\[
\sum_{m,j,i} \sum_{t \in T} X_{gmiij}(t, t') \geq csl_{ij} \sum_{m \in M_t} d_{m(i)} Y_i \\
(r, g) \in \Omega \land i \in I_c \land t \in T
\]

(4)

\[
\sum_{j; (m, i) \in F_t} \sum_{t \in T} X_{rgmiij}(t, t') = \sum_{i \in I_t} \sum_{r, t \in T} R_{ft} \beta_{min} X_{rgmiij}(t, t' - \phi_{r}) \\
(r, g) \in \Omega \land (m, i) \in \tilde{V}_c \land t \in T
\]

(5)

\[
\sum_{j \in I_c \land t \in T} X_{rgmiij}(t, t') \leq (1 - \alpha_m) \sum_{i \in I_t} \sum_{r, t \in T} \beta_{min} X_{rgmiij}(t, t' - \phi_{r}) \\
(r, g) \in \Omega \land (m, i) \in \tilde{V}_c \land t \in T
\]

(6)

\[
X_{rgmiij} = g^i_{j} Y_i \quad (r, g) \in \Omega \land (i, j) \in A_2 \land \tilde{t} : (t, t') \in \hat{T}
\]

(7)

\[
X_{rgmiij} \geq g^i_{j} Y_i \quad (r, g) \in \Omega \land (i, j) \in A_2 \land \tilde{t} : (t, t') \in \hat{T}
\]

(8)

\[
S_{rgmii} = g^i_{j} Y_i \quad (r, g) \in \Omega \land i \in I \land \tilde{t} : (t, t') \in \hat{T}
\]

(9)

\[
E_{rgii} = E_{rgj} \quad (r, g) \in \Omega \land (i, j) \in A \land \tilde{t} : (t, t') \in \hat{T}
\]

(10)

\[
E_{rgii} \leq \text{BigMY}_{ij} \quad (r, g) \in \Omega \land (i, j) \in A \land \tilde{t} : (t, t') \in \hat{T}
\]

(11)

\[
E_{rgii} \leq \text{BigMY}_{j} \quad (r, g) \in \Omega \land (i, j) \in A \land \tilde{t} : (t, t') \in \hat{T}
\]

(12)

Eqs. (2), (3) and (5)–(9) are similar to the ones of the deterministic model (Salema et al., 2010). Nevertheless, in the present formulation, constraints are established for each scenario (r,g). Eq. (2) imposes the material balance for all entities and for the entire set of products. This equation ensures that the inbound stock flow equals the sum of the outbound flow plus the difference between the existing and the new retained stocks. Given that the material balance is performed in terms of the type of product that leaves the entity, the product flow arriving at entities is translated into outbound flow by means of the parameter \( \beta_{min} \), which establishes the relationship between both types of flows. It is important to note that the discrete return levels at the customers are taken into account through parameter \( R_{frm} \). This corresponds to the return fraction of the final product \( m \) at quantity level \( r \). Eq. (3) enforces the demand satisfaction when customers are selected to enter the network. Eq. (4) imposes the minimum level of demand satisfaction. Thus, the amount of product delivered to customer \( i \) during a given macro-period \( t \) must be at least as large as the \( csl_{i} \) percentage of the demand for the period. Eq. (5) guarantees customer returns. The total quantity of returned products available at each customer depends on the supplied amount, which is translated into outbound flow by means of the parameter \( \beta_{min} \) and affected by the return fraction of the final product \( m \) at return level \( r \). Constraint (6) imposes the legislation targets for the recovering of materials. The parameter \( \alpha_m \) is the recovery minimum target for product \( m \), which is established by environmental regulatory policies. Thus, disassembly centres can only discard less than the fraction \( 1 - \alpha_m \) of the collected products. Constraints (7) and (8) model maximum and minimum limits for supplied amounts. Constraint (9) limits the storage capacity in factories, warehouses and sorting centers. Constraints (10)–(12) limit the maximum and minimum amount of products \([|h_{rpg(i)}|]\) that flow between entities \( i \) and \( j \), at time \( t \), for each scenario \((r,g)\). Bounds are modeled using the semi-continuous variable characteristics. Thus, the \( E_{rgij} \) variables can either be 0, or can behave as continuous variables between lower and upper limit values for the flows.

4. Case study description

An example based on a Portuguese glass company (Salema et al., 2010) is solved. In this work, the design and plan of the forward and reverse networks of a glass firm is addressed considering uncertainty on the quality and quantity of the return flows. A planning period of 5-year horizon is considered. The macro-time unit is assumed as 1 year and in turn this unit is divided into 6 intervals (micro-times of 2 months).

The closed-loop supply chain super-structure is composed of 4 factories, 8 warehouses, 18 customers, and 8 sorting centers. This firm has a factory in Leiria with a supplying contract of raw materials. Factories receive two types of raw materials (\( M_1 \) and \( M_2 \)) in order to produce three different types of glassware (\( F_1 \), \( F_2 \) and \( F_3 \)). These products are sent to warehouses where postproduction operations (i.e., packaging) are executed resulting in six different final products (\( A_1 \)–\( A_6 \)). Customers require the six products that are selectively supplied. Demand amounts for the products leaving the warehouses vary with the customer. The demand by customer for the planning period is given in Table 1. After use, customers send part of the received products (\( A_1 \)–\( A_6 \)) to the sorting centers. Each \( A \) product has an associated return fraction. Sorting centers classify the returned products, separating glass into two types (white and non-white glass, designated \( C_1 \) and \( C_2 \)) with different quality levels. It is assumed that sorting centers classify the returns in three quality grades (Good, Medium and Bad). Based on the quality grade the return products are sent to the factories, for incorporation into the new products, or sent back to disposal, in which case the fraction of these products must not exceed a legal target of 20% on the recovered amounts. No distinction is made between new and remanufactured products. Fig. 1 shows a schematic representation of product flows in the CLSC.

In this work, while the recovery target (\( \alpha \)) is assumed as a deterministic parameter, with a value of 0.80, the uncertain quality of returns sent to factory is approximated by five possible outcomes: Best (g1), Better (g2), Average (g3), Worse (g4) and Worst (g5). Each outcome is in turn a mix of the three quality grades, called Good, Medium and Bad, resulting of the classification process at the sorting centers. Outcomes and grading levels are taken as suggested in Denizel et al. (2010) for the remanufacturing planning of semiconductors. Table 2 shows the occurrence probability of each outcome and the percentage of return products of each quality grade. As it can be seen, the Better category assumes that 66.7% of the graded products are Good, 33.3% are Medium and 0% are Bad.

As referred above, the returns from customers (\( C_2 \) and \( C_1 \)) are classified at the sorting centers before being sent to the factories. Since the returned products compete with raw materials through integration into the processing of new products, their composition and cost are critical system parameters. Table 3 completes the problem data by showing the raw material and graded product prices in arbitrary currency units (c.u.).

The uncertain quantity of products returned by customers is approximated by three possible return levels: Optimistic (r1), Moderate (r2) and Pessimistic (r3). Table 4 shows the customers’ return fractions of final products and the occurrence probability of each level. It is worth noting that these values remain constant during the 5-year horizon. In addition, Table 4 shows the product price for
Table 1
Customer demands.

<table>
<thead>
<tr>
<th>Customer</th>
<th>Final products [10^3 m.u.]</th>
<th>A1</th>
<th>A2</th>
<th>A3</th>
<th>A4</th>
<th>A5</th>
<th>A6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Av (Aveiro)</td>
<td>1592</td>
<td>793</td>
<td>807</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Be (Beja)</td>
<td>147</td>
<td>269</td>
<td>478</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Br1 (Braga)</td>
<td>1511</td>
<td>277</td>
<td>475</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Br2 (Bragança)</td>
<td>291</td>
<td>167</td>
<td>186</td>
<td></td>
<td></td>
<td>269</td>
<td>483</td>
</tr>
<tr>
<td>CB (CBranco)</td>
<td>346</td>
<td>54</td>
<td>609</td>
<td></td>
<td></td>
<td>178</td>
<td>1021</td>
</tr>
<tr>
<td>Co (Coimbra)</td>
<td>356</td>
<td>217</td>
<td>983</td>
<td></td>
<td></td>
<td>1339</td>
<td>605</td>
</tr>
<tr>
<td>Ev (Evora)</td>
<td>382</td>
<td>301</td>
<td>179</td>
<td></td>
<td></td>
<td>295</td>
<td>558</td>
</tr>
<tr>
<td>Fa (Faro)</td>
<td>128</td>
<td>244</td>
<td>441</td>
<td></td>
<td></td>
<td>1197</td>
<td>487</td>
</tr>
<tr>
<td>Gu (Guarda)</td>
<td>191</td>
<td>181</td>
<td>478</td>
<td></td>
<td></td>
<td>290</td>
<td>513</td>
</tr>
<tr>
<td>Le (Leiria)</td>
<td>148</td>
<td>181</td>
<td>478</td>
<td></td>
<td></td>
<td>1048</td>
<td>974</td>
</tr>
<tr>
<td>Lxa (Lisboa)</td>
<td>4071</td>
<td>3795</td>
<td>1103</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Po2 (Portalegre)</td>
<td>3492</td>
<td>596</td>
<td>3171</td>
<td>2581</td>
<td>1026</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Po1 (Porto)</td>
<td>126</td>
<td>59</td>
<td>534</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sa (Santarem)</td>
<td>175</td>
<td>1084</td>
<td>725</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Se (Setubal)</td>
<td>4031</td>
<td>816</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VC (VCastelo)</td>
<td>445</td>
<td>249</td>
<td>249</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VR (Vreal)</td>
<td>325</td>
<td>64</td>
<td>629</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vi (Viseu)</td>
<td>923</td>
<td>152</td>
<td>1057</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Fig. 1. Product flow in the CLSC.

Table 2
Grading levels for the returned products.

<table>
<thead>
<tr>
<th>Grading outcomes</th>
<th>Prob.</th>
<th>% Good</th>
<th>% Medium</th>
<th>% Bad</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best (g1)</td>
<td>0.05</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Better (g2)</td>
<td>0.20</td>
<td>66.7</td>
<td>33.3</td>
<td>0</td>
</tr>
<tr>
<td>Average (g3)</td>
<td>0.50</td>
<td>33.3</td>
<td>33.3</td>
<td>33.4</td>
</tr>
<tr>
<td>Worse (g4)</td>
<td>0.15</td>
<td>0</td>
<td>33.3</td>
<td>66.7</td>
</tr>
<tr>
<td>Worst (g5)</td>
<td>0.10</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3
Raw material and graded product prices.

<table>
<thead>
<tr>
<th></th>
<th>Unit product price</th>
<th>C1</th>
<th>C2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw material</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Graded products</td>
<td>Good</td>
<td>0.045</td>
<td>0.060</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>0.045</td>
<td>0.060</td>
</tr>
<tr>
<td></td>
<td>Bad</td>
<td>0.080</td>
<td>0.115</td>
</tr>
</tbody>
</table>

final products (A1 – A6) that have a commercialization price allowing the company to obtain revenues and to be competitive in comparison with others in the same market sector. Company’s historical data on the quality and quantity of the return flows were not available. Therefore, the parameter values for scenario outcomes and their probabilities have been carefully selected in order to study a representative case of the company operation.

5. Numerical results

Several instances of the Portuguese glass company example are solved in order to investigate the impact on the CLSC design and planning when changes in parameters associated with the quality and quantity of the return flows are performed. The mathematical formulation was implemented in GAMS 23.6.3 and solved with CPLEX 12.2, on a laptop with Intel Core i7 Q740 1.73 GHz and 8 GB RAM memory for a 0.001% gap tolerance. The 8 threads associated
with the 4 cores of the processor were available for processing in all cases.

5.1. Results for different levels of the return quality

To illustrate the effects of different levels of the return quality, five cases have been solved. The instances show the consequences of the diverse outcomes considered (Best, Better, Average, Worse and Worst) when the three possible return levels are simultaneously taken into account.

Tables 5 and 6 show the main optimal network results and the CLSC structure for the five different cases, respectively. By comparison with the super-structure, the entities belonging to the optimal network for each case are indicated by “×”. As it can be seen in the tables, the quality of the returned products to the factory assumes a great importance when maximizing the network profit. Thus, the larger network structure (3 factories, 3 warehouses, 18 costumers and 5 sorting centers) with higher profit is obtained when considering that 100% of the returned products are of Good quality (case g1–(r1–r3)). The network size decreases as the quality declines, reaching its minimum (3 factories, 3 warehouses, 16 costumers and 3 sorting centers) for case g5–(r1–r3). From case g1–(r1–r3) to g5–(r1–r3) the network structure suffers modifications on the number of customers (C) and sorting centers (S). In addition, while for instances g3–(r1–r3) and g4–(r1–r3) the network configuration remains unchanged, the expected profit is significantly modified due to a minor reduction of the expected sales and a marked increment in the expected cost. Table 5 also shows that when the quality decreases, the customer satisfaction level and product unit cost change. While the former drops from 99.3% to 81.9%, the latter rises from 0.00154 to 0.00267 currency units. These variations are mainly produced by the graded product prices (see Tables 2 and 3).

Table 7 and Fig. 2 show the reverse network indicators and the supply chain flows: suppliers to factories (F), factories to warehouses (equal to warehouses to customers) (F–W–C), customers to sorting centers (C–S), customers to disposal (C–D) and sorting centers to factories (S–F), as well as sorting centers to disposal (S–D), for the different return qualities. It is important to note that, in order to compare the flows between different pair of entities, all of them are stated in terms of raw material.

As it can be seen in Table 7, in the sorting centers (S–F), cases g1–(r1–r3) and g2–(r1–r3) the recovery levels are 99.1% and 94.2%, respectively, that are greater than the 80% legal target. On the contrary, for cases g3–(r1–r3) to g5–(r1–r3) the recovery volume is

<table>
<thead>
<tr>
<th>Return levels</th>
<th>Prob.</th>
<th>Final products</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A1</td>
</tr>
<tr>
<td>Optimistic (r1)</td>
<td>0.35</td>
<td>0.55</td>
</tr>
<tr>
<td>Moderate (r2)</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>Pessimistic (r3)</td>
<td>0.20</td>
<td>0.35</td>
</tr>
<tr>
<td>Unit price</td>
<td></td>
<td>0.30</td>
</tr>
</tbody>
</table>

### Table 5
Main optimal network results for different grading levels.

<table>
<thead>
<tr>
<th></th>
<th>Max F (c.u.)</th>
<th>Expected sale (c.u.)</th>
<th>Expected cost (c.u.)</th>
<th>Customers satisfaction level (%)</th>
<th>Prod. unit cost (10⁻³ c.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>g1–(r1–r3)</td>
<td>7356.7</td>
<td>15965.9</td>
<td>8609.2</td>
<td>99.3</td>
<td>1.54</td>
</tr>
<tr>
<td>g2–(r1–r3)</td>
<td>6147.9</td>
<td>15570.6</td>
<td>9422.7</td>
<td>92.5</td>
<td>1.74</td>
</tr>
<tr>
<td>g3–(r1–r3)</td>
<td>4003.7</td>
<td>15515.9</td>
<td>11532.2</td>
<td>92.3</td>
<td>2.14</td>
</tr>
<tr>
<td>g4–(r1–r3)</td>
<td>2098.8</td>
<td>15380.3</td>
<td>13281.5</td>
<td>89.7</td>
<td>2.49</td>
</tr>
<tr>
<td>g5–(r1–r3)</td>
<td>1187.9</td>
<td>14834.5</td>
<td>13646.6</td>
<td>81.9</td>
<td>2.67</td>
</tr>
</tbody>
</table>

c.u. is currency arbitrary units.

### Table 6
Optimal network structures for different grading levels.

<table>
<thead>
<tr>
<th>Super-structure</th>
<th>g1–(r1–r3)</th>
<th>g2–(r1–r3)</th>
<th>g3–(r1–r3), g4–(r1–r3)</th>
<th>g5–(r1–r3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F W S C</td>
<td>F W S C</td>
<td>F W S C</td>
<td>F W S C</td>
<td>F W S C</td>
</tr>
<tr>
<td>Av (Aveiro)</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Be (Beja)</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Br1 (Braga)</td>
<td>× × ×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Br2 (Bragança)</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>CB (Cibrancos)</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Co (Coimbra)</td>
<td>× × ×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Ev (Evora)</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Fa (Faro)</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Gu (Guadalh)</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Le (Leiria)</td>
<td>× × × ×</td>
<td>× × × ×</td>
<td>× × × ×</td>
<td>× × × × ×</td>
</tr>
<tr>
<td>Lxa (Lisboa)</td>
<td>× × × ×</td>
<td>× × × ×</td>
<td>× × × ×</td>
<td>× × × × ×</td>
</tr>
<tr>
<td>Po2 (Portalegre)</td>
<td>× × ×</td>
<td>× × × ×</td>
<td>× × × ×</td>
<td>× × × × ×</td>
</tr>
<tr>
<td>Po1 (Porto)</td>
<td>× × × ×</td>
<td>× × × ×</td>
<td>× × × ×</td>
<td>× × × × ×</td>
</tr>
<tr>
<td>Sa (Santarem)</td>
<td>× ×</td>
<td>× × ×</td>
<td>× × × ×</td>
<td>× × × × ×</td>
</tr>
<tr>
<td>Se (Setubal)</td>
<td>× × ×</td>
<td>× × ×</td>
<td>× × × ×</td>
<td>× × × × ×</td>
</tr>
<tr>
<td>VC (Vilela)</td>
<td>× ×</td>
<td>× × ×</td>
<td>× × × ×</td>
<td>× × × × ×</td>
</tr>
<tr>
<td>VR (Vimeir)</td>
<td>× ×</td>
<td>× × ×</td>
<td>× × × ×</td>
<td>× × × × ×</td>
</tr>
<tr>
<td>Vi (Viseu)</td>
<td>× × ×</td>
<td>× × × ×</td>
<td>× × × ×</td>
<td>× × × × ×</td>
</tr>
<tr>
<td>TOTAL</td>
<td>5 8 8 18</td>
<td>3 3 5 18</td>
<td>3 3 4 17</td>
<td>3 3 3 17</td>
</tr>
</tbody>
</table>

Table 7
Reverse network indicators for different grading levels.

<table>
<thead>
<tr>
<th>Max disposal (m.u.)</th>
<th>Actual disposal (S–D) (m.u.)</th>
<th>Actual disposal (%)</th>
<th>Min recovery (m.u.)</th>
<th>Total return (C–S) (m.u.)</th>
<th>Actual recovery (S–F) (m.u.)</th>
<th>Actual recovery (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>g1–(r1–r3)</td>
<td>15713.4</td>
<td>679.4</td>
<td>4.3</td>
<td>62851.5</td>
<td>78566.9</td>
<td>77887.4</td>
</tr>
<tr>
<td>g2–(r1–r3)</td>
<td>15148.5</td>
<td>4413.8</td>
<td>29.1</td>
<td>60593.9</td>
<td>75742.4</td>
<td>71328.6</td>
</tr>
<tr>
<td>g3–(r1–r3)</td>
<td>15092.8</td>
<td>15092.8</td>
<td>100.0</td>
<td>60371.1</td>
<td>75463.9</td>
<td>60371.1</td>
</tr>
<tr>
<td>g4–(r1–r3)</td>
<td>14854.5</td>
<td>14854.5</td>
<td>100.0</td>
<td>59417.9</td>
<td>74272.4</td>
<td>59417.9</td>
</tr>
<tr>
<td>g5–(r1–r3)</td>
<td>14067.5</td>
<td>14067.5</td>
<td>100.0</td>
<td>56270.0</td>
<td>70337.5</td>
<td>56270.0</td>
</tr>
</tbody>
</table>

m.u. is mass arbitrary unit.

Fig. 2. Resulting flows of different grading levels.

at its allowed minimum. Fig. 2 shows that the flows of products from factories to customers (passing through warehouses) (F–W–C) drop when the quality decreases. The reduction is mainly due to the decrease of the S–F flows and it takes place in spite of the increment of the raw material requirements.

5.2. Results for diverse return levels

To illustrate the effects of distinct return levels, three cases were solved. These instances are associated with the customers’ return levels when the five quality outcomes are considered altogether. The results obtained are presented in Tables 8–10 and Fig. 3.

Fig. 4. Forward and reverse networks of instance ST.
Table 8
Main optimal network results for different return levels.

<table>
<thead>
<tr>
<th></th>
<th>Max $F$ (c.u.)</th>
<th>Expected sale (c.u.)</th>
<th>Expected cost (c.u.)</th>
<th>Network installation cost (c.u.)</th>
<th>Reprocessing cost (c.u.)</th>
<th>Customers satisfaction level [%]</th>
<th>Prod. unit cost (c.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>r1-(g1-g5)</td>
<td>3696.2</td>
<td>15453.6</td>
<td>11757.4</td>
<td>950.0</td>
<td>3912.59</td>
<td>91.1</td>
<td>0.00019</td>
</tr>
<tr>
<td>r2-(g1-g5)</td>
<td>4117.0</td>
<td>15509.9</td>
<td>11392.9</td>
<td>850.0</td>
<td>3398.82</td>
<td>91.9</td>
<td>0.00021</td>
</tr>
<tr>
<td>r3-(g1-g5)</td>
<td>4435.8</td>
<td>15551.6</td>
<td>11115.9</td>
<td>850.0</td>
<td>2848.84</td>
<td>92.5</td>
<td>0.00206</td>
</tr>
</tbody>
</table>

c.u. is currency arbitrary units.

Table 9
Optimal network structures for different return levels.

<table>
<thead>
<tr>
<th></th>
<th>r1-(g1-g5)</th>
<th></th>
<th>r2-(g1-g5), r3-(g1-g5)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$F$ (m.u.)</td>
<td>$W$ (m.u.)</td>
<td>$S$ (m.u.)</td>
</tr>
<tr>
<td>Av (Aveiro)</td>
<td>$\times$</td>
<td></td>
<td>$\times$</td>
</tr>
<tr>
<td>Be (Beja)</td>
<td></td>
<td>$\times$</td>
<td></td>
</tr>
<tr>
<td>Br1 (Braga)</td>
<td>$\times$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Br2 (Bragança)</td>
<td>$\times$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB (Cávado)</td>
<td></td>
<td>$\times$</td>
<td></td>
</tr>
<tr>
<td>Co (Viseu)</td>
<td>$\times$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ev (Eva)</td>
<td></td>
<td></td>
<td>$\times$</td>
</tr>
<tr>
<td>Fa (Faro)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gu (Guarda)</td>
<td>$\times$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Le (Leiria)</td>
<td></td>
<td></td>
<td>$\times$</td>
</tr>
<tr>
<td>Lx (Lisboa)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P&amp;O (Porto)</td>
<td>$\times$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S (Santarém)</td>
<td></td>
<td></td>
<td>$\times$</td>
</tr>
<tr>
<td>Se (Setúbal)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V (Vila Real)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Va (Viseu)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>3</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 10
Optimal network structure for different return levels.

<table>
<thead>
<tr>
<th></th>
<th>Max disposal (S-D) (m.u.)</th>
<th>Actual disposal (S-D) (m.u.)</th>
<th>Actual disposal (%)</th>
<th>Min recovery (S-F) (m.u.)</th>
<th>Total return (S-F) (m.u.)</th>
<th>Actual recovery (S-F) (m.u.)</th>
<th>Actual recovery (S-F) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>r1-(g1-g5)</td>
<td>17120.6</td>
<td>14987.8</td>
<td>87.5</td>
<td>68482.4</td>
<td>85603.0</td>
<td>70615.2</td>
<td>82.5</td>
</tr>
<tr>
<td>r2-(g1-g5)</td>
<td>14694.3</td>
<td>11929.3</td>
<td>81.2</td>
<td>58777.2</td>
<td>73471.5</td>
<td>61542.2</td>
<td>83.8</td>
</tr>
<tr>
<td>r3-(g1-g5)</td>
<td>12179.9</td>
<td>9129.2</td>
<td>75.0</td>
<td>48719.8</td>
<td>60899.7</td>
<td>51770.5</td>
<td>85.0</td>
</tr>
</tbody>
</table>

m.u. is mass arbitrary units.

Table 8 shows that the objective function, the customer satisfaction level and the unit cost of production deteriorate, when the return level increases from r3-(g1-g5) to r1-(g1-g5). This increase, that might be conceived as a result of a greater consumers’ awareness, aggravates all operational costs and requires an additional investment, i.e. a new sorting centre, thus narrowing the network profit margin. Hence a lower profit is achieved that comes also associated with a reduction, albeit small, in customers’ satisfaction.

In terms of network structure, Table 9 displays the number of entities in the network, which is greater in case r1-(g1-g5). Thus, while the number of factories, warehouses and customers is equal for the three return levels, the number of sorting centers changes: 4 for r1-(g1-g5), i.e. Optimistic case, and 3 for the remaining two cases (Moderate and Pessimistic).

The effects on the network flows are shown in Table 10 and Fig. 3. As it can be seen in Table 10, considering the disposal volume (S-D), the three cases, r3-(g1-g5) to r1-(g1-g5), assume disposal levels within the legal target of 80% of the total return. The effect of an increasing return level is again visible: the degree of the actual recovery decreases in tandem with an increase in disposal, which comes closer, i.e. within 87.5%, to the legal target. As it can be seen in Fig. 3, this effect that is accompanied by a decrease in customers’ disposal (C-D), influences markedly the pattern of flows along the network. A larger volume of returns is sent to factory (S-F), which now requires a lower input of raw materials (F) to meet the supply needs to customers (F-W-C). Case r3-(g1-g5) describes the opposite situation, while r2-(g1-g5) which is the closest to the base case, ST (see next section), embodies a compromise between these two.

5.3. Results obtained when the quantity and quality of the returns are simultaneously considered

In this section, the results of the stochastic case (ST) with 15 possible scenarios (3 return levels × 5 grading outcomes) are shown. The obtained network structure and the links between different pairs of entities are illustrated in Fig. 4. The solution for the instance ST, by contrast with cases g1-(r1-r3) to g5-(r1-r3) and r1-(g1-g5) to r3-(g1-g5), is found to be equal to g3-(r1-r3), g4-(r1-r3), r2-(g1-g5) and r3-(g1-g5) in terms of the number and location of entities (3 factories, 3 warehouses, 17 costumers and 3 sorting centers).

In terms of flows, the ST instance is similar to g3-(r1-r3) and r2-(g1-g5) (see Fig. 5). Nevertheless, considering cases g3-(r1-r3) and r2-(g1-g5), ST exhibits the smallest F flow and customer satisfaction level (a value of 91.4% is obtained), as well as the greatest S-F flow. In addition, by comparison with case g3-(r1-r3), ST displays
greater values for profit (4022.2 c.u.), expected revenue (15475.7 c.u.), expected cost (11453.5 c.u.) and percentage of actual recovery (82.9%), as well as a smaller production unit cost (0.00213 c.u.).

6. Computational statistics

Table 11 shows the computational statistics for the cases solved for a 0.001% gap tolerance. All model dimensions for similar types of instances are the same. In terms of computational time, the first group of scenarios takes on average about 312 min while the last one which has the largest instances takes on average about 808 min.

The model is found to be extremely computationally intensive, which from a problem-solving point of view, represents a considerable challenge because the model size (in terms of number of variables and constraints) increases with the number of scenarios.

It is important to note that the computational statistics shown in Table 11 were obtained under default parameters of GAMS/Cplex. In addition, the examples were also solved considering different values for two parameters associated with preprocessing and general options, such as Lpmethod and threads. While Lpmethod specifies which linear programming (LP) algorithm will be used, the parameter threads sets the number of parallel threads allowed for the solution method. Nevertheless, the best average performance was obtained considering the default options of GAMS/Cplex, which take into account that the LP method employed is selected automatically and the threads are determined for GAMS. In a future work, other parameters will be considered in order to reduce the computational times.

Table 11

<table>
<thead>
<tr>
<th>Cases</th>
<th>Variables</th>
<th>Constraints</th>
<th>CPU (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>Binary</td>
<td>Semi-continuous</td>
</tr>
<tr>
<td>g1-(r1-r3)</td>
<td>261,823</td>
<td>38</td>
<td>33,120</td>
</tr>
<tr>
<td>g2-(r1-r3)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>g3-(r1-r3)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>g4-(r1-r3)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>g5-(r1-r3)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>r1-(g1-g5)</td>
<td>436,317</td>
<td>38</td>
<td>55,200</td>
</tr>
<tr>
<td>r2-(g1-g5)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>r3-(g1-g5)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ST</td>
<td>1,308,787</td>
<td>38</td>
<td>165,600</td>
</tr>
</tbody>
</table>

Fig. 5. Resulting flows of instances ST, g3-(r1-r3) and r1-(g1-g5).

7. Conclusions

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

The formulation relevance was evaluated by an example based on an industrial case that involves the CLSC of a Portuguese glass firm. Through the numerical tests obtained with the proposed approach for different cases, the relative impact of the uncertainty on the structure, planning and cost of the CLSC were analyzed.

From the results obtained, some important aspects of the CLSC are revealed. Thus it is found that an increase in the returns quality, i.e. cases g5-(r1-r3) to g1-(r1-r3), improves the profitability and the overall performance of the network, which becomes less reliant on raw material and sends an almost negligible amount of returns to disposal. The only adverse effect is the increase observed in the customers direct product disposal (C-D), since they are meant to respond only in terms of the quantity of product received, which increases with quality.

As regards the returns quantity, i.e. cases r3-(g1-g5) to r1-(g1-g5), this work was instrumental in casting light on an important characteristic of the CLSC: its operation is oriented towards the profitable handling of returns, but under the strict legal condition of not exceeding a preset target of 20% disposal.

As the quantities of returns increase, all the operational costs are also found to increase, together with some additional investment, and hence the profitability is reduced. Conceivably there could be a level of returns, which would make this network no longer profitable, unless some of its basic assumptions were to be reviewed.

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

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Appendix A.

Sets

Entities:

\( I_f \) possible locations for factories,
\( I_w \) possible locations for warehouses,
\( I_k \) locations of customers,
\( I_d \) possible locations for disassembly centers,
\( I_o \) disposal option.

Products:

\( M_f \) factories outbound products,
\( M_w \) warehouses outbound products,
\( M_k \) customers outbound products,
\( M_d \) disassembly centers outbound products.

Scenarios:

\( R \) return levels of final products, \( r \in R \),
\( G \) outcomes of the grading process (grading outcomes), \( g \in G \),
\( Q \) quality categories of products obtained as result of sorting centers operations, \( q \in Q \),
\( \Omega = \{(r, g) : r \in R \land g \in G\} \).

Products-entities:

\( V_f = \{(m, i) : m \in M_f \land i \in I_f\} \),
\( V_a = \{(m, i) : m \in M_a \land i \in I_a\} \),
\( V_k = \{(m, i) : m \in M_k \land i \in I_k\} \),
\( V_d = \{(m, i) : m \in M_d \land i \in I_d\} \),
\( V = V_f \cup V_a \cup V_k \cup V_d \).

Flows:

\( A_R = \{(i, j) : i \in I_f \land j \in I_k\} \),
\( A_{R+} = \{(i, j) : i \in I_k \land j \in I_f\} \),
\( A_{R-} = \{(i, j) : i \in I_w \land j \in I_k\} \),
\( A_{R+} = \{(i, j) : i \in I_k \land j \in I_w\} \),
\( A_d = \{(i, j) : i \in I_l \land j \in I_o\} \).

Time:

\( T \) macro-times,
\( T^\prime \) micro-times,
\( \bar{T} = \{(t, t^\prime) : t \in T \land t^\prime \in T^\prime\} \) all time units.

Products-flows:

\( F_R = \{(m, i, j) : m \in M_f \land (i, j) \in A_R\} \),
\( F_{R+} = \{(m, i, j) : m \in M_k \land (i, j) \in A_{R+}\} \),
\( F_{R-} = \{(m, i, j) : m \in M_a \land (i, j) \in A_{R-}\} \),
\( F_{R+} = \{(m, i, j) : m \in M_d \land (i, j) \in A_{R+}\} \),
\( F_d = \{(m, i, j) : m \in M_d \land (i, j) \in A_d\} \).

Parameters

\( \tau_{ij} \) travel time between entities \( i \) and \( j \),
\( \phi_m \) processing/usage time of product \( m \),
\( \xi_{mi} = \tau_{ij} \phi_m \) function of both travel and processing times, giving the earliest micro-time unit a flow of product \( m \) with origin in entity \( i \), may occur.

\( \alpha_m \) recovery target for product \( m \) set by legislation, \( \alpha_m \in [0, 1] \),
\( \beta_{min} \) relation between product \( m \) and \( m_i \),
\( s_{min} \) initial stock of product \( m \) in entity \( i \),
\( f_i \) investment cost of entity \( i \),
\( c_i \) cost of leaving customer \( i \) out of the supply chain,
\( g_i \) maximum storage capacity of entity \( i \),
\( h_i \) maximum and minimum supplying limit of entity \( i \),
\( h_{ij} \) upper bound value for flows connecting entities \( i \) and \( j \),
\( h_{ij} \) lower bound value for flows connecting entities \( i \) and \( j \),
\( RF_{min} \) return fraction of final product \( m \) at level \( r \). This parameter adapts the value one when \( m \neq M_c \),
\( P_x \) occurrence probability of the grading outcome \( g \),
\( P_x \) occurrence probability of the return level \( r \).

Macro-time parameters:

\( d_{mit} \) product \( m \) demand for entity \( i \) for macro-period \( t \), \( i \in I \),
\( c^m_{mit} \) unit variable cost of non-satisfied demand/return of product \( m \) to entity \( i \) for macro-period \( t \).
\( cs_{it} \) satisfaction level of customer \( i \) (\( i \in I \)) for macro-period \( t \).

Micro-time parameters:

\( c_{mij} \) unit transportation cost of product \( m \) from entity \( i \) to entity \( j \) at time \( t \),
\( c^m_{mit} \) unit storage cost at entity \( i \) at time \( t \),
\( v_{mi} \) unit price of product \( m \) (\( m \in M \)) at time \( t \),
\( c_{mij} \) unit cost of quality category \( q \) of returned product \( m \) from entity \( i \) to entity \( j \) at time \( t \),
\( fr_{gqmi} \) fraction of quality \( q \) of grading category \( g \) of product \( m \) from entity \( i \), to entity \( j \), at time \( t \).

Continuous variables

\( X_{gmit} \) amount of product \( m \) transported from entity \( i \) to entity \( j \), at time \( t \), at scenario \((r, g)\) corresponding to return level \( r \) and grading outcome \( g \),
\( S_{gmit} \) amount of product \( m \) stored in entity \( i \), at period \( r \), at scenario \((r, g)\),
\( U_{gmit} \) non-satisfied amount of product \( m \) in customer \( i \), over macro-period \( t \), at scenario \((r, g)\).

Binary variables

\( Y_i \) entity \( i \) opened/served,

Semi-continuous variable

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

References


