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# **Finding best practices for automotive glazing recycling: a network optimization model**

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## NOMENCLATURE

### Subscripts

d	Dismantling procedure/unit
s	Storage site
r	Treatment unit
m	Market for cullet
i	Any procedure/unit

### Design variables

$W_d$	Quantity of ELV transferred to dismantling unit $d$
$W_{out}$	Quantity of ELV of no glazing dismantling
$X_{ds}$	Quantity of glazing transformed from dismantling unit $d$ to storage site $s$
$L_d$	Quantity of glazing exposed to landfill
$\bar{L}_d$	Total quantity of glazing exposed to landfill
$Y_{sr}$	Quantity of glazing transformed from store site $s$ to treatment unit $r$
$Z_{rm}$	Quantity of cullet produced from treatment unit $r$ to market $m$

### Quality constraints

$x_{ds}$	Is 1 If the dismantled glazing of $d$ is eligible for storage site $s$ , otherwise 0.
$y_{sr}$	Is 1 If the stored batch of $s$ is eligible for treatment unit $r$ , otherwise 0.
$z_{rm}$	Is 1 If the treated cullet of $r$ is eligible for market $m$ , otherwise 0

### Model parameters

$W$	N°	Number of ELV going to general valorization network
$\rho$	Ton	Weight of glass per ELV = 0.042 ton
$\rho_d$	Ton	Weight of glass produced by dismantling procedure $d$
$\tau_d$	%	Yield of dismantling procedure $d$ ( $= \rho_d/\rho$ )
$C_{Dd}$	€	Unit cost for dismantling procedure $d$
$\hat{C}_D$	€	Average unit cost for dismantling procedure
$\mu_d$		Dismantling procedure cost coefficient for procedure $d$
$C_{Ld}$	€	Unit cost for landfill of non-dismantled glazing procedure $d$
$\hat{C}_L$	€	Average unit cost for landfill banal waste
$C_{COLds}$	€	Unit cost for collecting glazing from dismantler $d$ to store site $s$
$\hat{C}_{COL}$	€	Average unit cost for collecting glazing to storage site
$\sigma_{ds}$		Cost coefficient for collecting from dismantler $d$ to store site $s$
$C_{STOds}$	€	Unit cost for storage
$\hat{C}_{STO}$	€	Average unit cost for storage

$C_{TRA_{sr}}$	€	Unit cost for transferring glazing from store $s$ to treatment unit $r$
$\hat{C}_{TRA}$	€	Average unit cost for transport glazing
$\delta_{sr}$		Cost coefficient for transport glazing from store $s$ to treatment unit $r$
$C_{TRE_r}$	€	Unit cost for treatment in unit $r$
$\gamma_r$		Production coefficient of treatment process $r$
$P_m$	€	Price of cullet in market $m$
$C_{Out}$	€	Cost of no glazing dismantling (e.g. penalty)
$H_i$		Capacity limit (number or tons) of unit $i$
$F_i$		Material transformation of process $i$

**INTRODUCTION**

Reuse, recycle and recovery of End of Life Vehicles (ELV) materials are increasingly of interest to researchers and industrial companies, mainly because of the application of an EU directive on ELV (EU-Directive 2000). The directive sets the ultimate goal of reuse and recovery at a rate of 95% of the ELV weight; furthermore, from 2015 on (EU-Directive 2000) certain materials including glass must be separated during dismantling from the ELV. Contrary to previous directives, this directive penalizes car manufacturers if target reuse and recovery rate is not reached.

Each year, 1.8 million End of Life Vehicles (ELV) are produced in France from different sources such as garages, insurance companies, car dealerships, and individuals according to the official French Environment and Energy Management Agency (ADEME) institution (ADEME 2008). Out of this amount, 80 to 90% goes to certified dismantling units, who are members of a national certified network. Despite a high rate of metal recycling (such as steel, copper and aluminum), the last official ADEME report shows the recycling and recovery process for low-value non-metallic materials such as plastics, textiles, foams, elastomeric seals and glass to be very limited, or even non-existent in France (ADEME 2008). In particular, the non-dismantled glass pieces (e.g. windshield) called the glazing during the dismantling phase is typically shredded with the ELV shell and sent to a landfill. This glass, mixed with other residuals and contaminated with organic substances, is practically unusable and has no market value.

Within the boundaries of this study, recycling ELV glazing is defined as the process of dismantling, collection, storage and transportation, treatment, and ultimately reuse of recycled glass called *cullet*. Cullet is regularly used for making glass products, glass wool, or as a substitution for other raw materials. Beyond the price advantage, each 10 % increase in cullet usage in a glass furnace results in a 2-3% energy saving in the melting process: and each ton of cullet used saves 230 kg of CO<sub>2</sub> emissions (Loredo, Martinez et al. 1986; Reindl 2003; Remade-Scotland 2003; Butler and Hooper 2005). This has created an increasing demand for high-quality cullet by the glass industry. However, neither the demand for cullet, nor that of post-consumer recycled glass, is satisfied by current supply (Wrap 2008).

Figure 1 shows an ELV glazing recycling network in the form of a directed acyclic graph of value chains linking stakeholders dedicated to specific activities. The stakeholders of this network are the car manufacturers, the ELV dismantlers and shredders, the collecting and transporting companies, and the glass treatment companies. If the glazing network is considered as a whole, the cost and benefit can be stated as follows: the costs arise from dismantling, collection and transportation, treatment, and the penalty paid by the producer in case of non-achievement of the directive target rate. The benefit of the network is from selling the produced cullet in the market, and the cost of not landfilling and shredding residual waste.

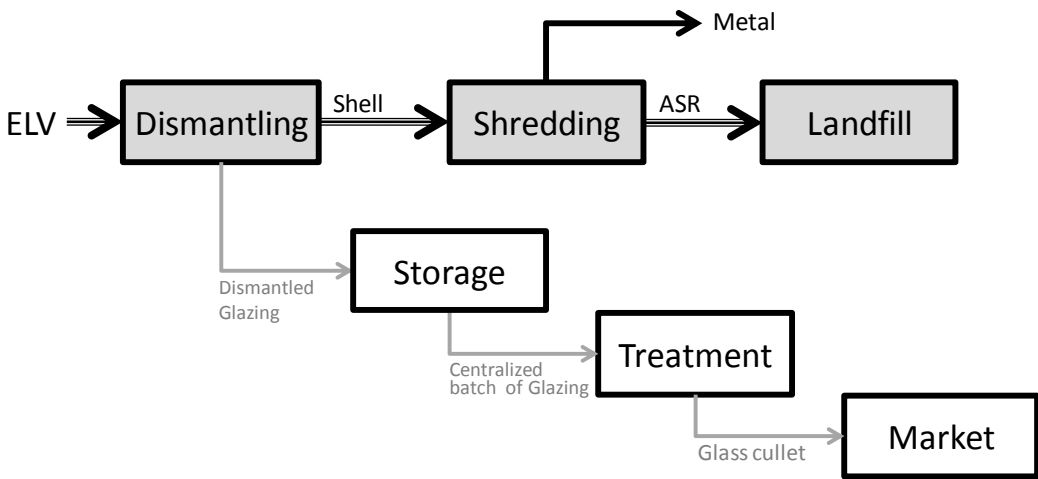


Figure 1. ELV glazing recycling scheme

For dismantlers, the interest to remove the glazing is questionable for two reasons. First, the dismantling procedure of glazing (itself) implies extra time and thus extra costs. After dismantling, the dismantled glass needs to be transported to a treatment unit, which costs more than the buyer can offer. Alternatively, the

dismantled glass can be transported to landfill, which has its own costs. Meanwhile, none of these extra costs are compensated (Gillot 2000; ADEME 2007).

Second, with a proven market demand for cullet, treatment of the dismantled glazing and sale of the cullet could potentially make a profit for treatment units and for the glass production industry (Glass 2009). However, in the absence of a large scale recycling network to share profit and finance the up-stream costs, it is not strategically justified for dismantlers to invest on a network with no future profit. Table 1 shows the motivations and disincentives of each stakeholder for a future ELV glazing recycling network.

Table 1. Individual motivation and disincentives of stakeholders for a future ELV glazing recycling network

	Individual motivation for recycling network	Disincentive for performing activity
<b>Car manufacturer</b>	Meet the 95% target and avoid penalty	None
<b>Dismantler</b>	Attain a higher dismantling rate and use commercial benefits and potential government subsidies	Extra cost
<b>Shredder</b>	Less landfill cost	None
<b>Collection and Transportation</b>	Improve the logistical operation	Volume issues
<b>Glass treatment</b>	Increase in feed and product flow	None
<b>Cullet buyer</b>	Satisfy the demand	Quality issues

Table 1 shows that the interests of stakeholders diverge. It is therefore difficult to establish the overall interest of the creation of this value chain. This is why we propose a Cost Benefit Analysis (CBA) of this value chain to make sure that the gains to the winners exceed the losses to the losers. This result will be employed to examine the possibility of a redistribution mechanism for benefits, assuring that being a member of recycling network is economically viable for each stakeholder.

The realization of material flow shown in figure 1 also represents the decisions of stakeholders, as they are the result of choices between several operational alternatives (e.g how to dismantle, how to store, how to treat). Therefore, developing an approach for decision support for the recycling network requires modeling the operation activities, and parameterizing each activity with associated costs and benefits.

The cost and benefit of each operation is subject to change, due to the change in cost and profit elements value. These changes are due to environmental policy changes, market changes, and changes in operating conditions. These changes influence the model behavior, and lead to a new topology for the network and new flow attribution. This paper identifies these key variables: cullet price, landfill cost, and penalty, and runs the optimization under a range of values. If the costs and benefits are expressed in a mathematical model, the optimum situation of the network for maximizing the profit can be found using programming techniques. In realizing a CBA, data collection is especially difficult when the network does not physically exist. A set of possible alternative tasks for each stakeholder activity in the recycling value chain must also be represented. The alternatives have to be parameterized in detail. For example, alternative dismantling procedures might end up with different qualities of dismantled glass, where costs vary. Each stakeholder must choose one of the considered alternatives within admissible technical limits.

This study provides a framework for discussing the alternative scenarios of stakeholder activity in a future glazing recycling network. A mathematical model is proposed to maximize the cost and benefit of the whole network, providing all the stakeholders behave in a coordinated and rational way. In a certain sense, it provides ideal cost-benefit scenarios within which stakeholder activities are optimally determined. A linear programming model is employed to obtain the optimal material flow of ELV glazing, going through the activity alternatives in

dismantling procedure, collection and storage sites, glass treatment units, and the final cullet product. Technical and economic data are gathered for a recycling network for ELV glazing envisaged in France in the near future – in about 3 years' time. Parameters and constraints are obtained from industrial and recycling professional partners in France. Total costs including fixed costs, transportation costs, final treatment costs as well as the revenue from selling glass cullet are included in the objective function.

The paper is organized as follows: Section 2 gives a brief review of ELV material recycling studies and proposed approaches. Section 3 presents the model structure and mathematical expression of the objective function and constraints. In Section 4 the technical and economic details of each activity are described, and then ground data, estimations and constraints of variables at the national level are presented. Section 5 sets out the results of network and flow optimization, extended by varying three values in seven scenarios, and the effect of each variable change on network topology and material flow is explained. The last section points out some extensions of the model in perspective.

## LITERATURE REVIEW

In a systematic research, Ilgin reviewed the environmentally conscious manufacturing and product recovery methods (Ilgin and Gupta 2010). The subject of ELV recycling improvement had been looked at by several researchers in previous decades. To provide a better understanding of the research focus, we divide these studies into four categories.

In the first category, various propositions are made that integrate recycling concerns into the design phase, such as methods and supporting tools for integrating the end of life reuse and recycling into the design phase (Gehin, Zwolinski et al. 2008), methodology to guide material choices during design (Froelich, Haoues et al. 2007), and product information for recycling (Duval and MacLean 2007).

In the second category, the focus is on the recycling activities, such as dismantling technologies (Suzuki, Sato et al. 2001), separation techniques (Malcolm Richard, Mario et al. 2011), and the problem of locating collection facilities and logistics costs (Vidovic, Dimitrijevic et al. 2011).

Studies in the third category focus on the recycling at the policy and strategy level. While regulation-driven changes in car recycling have been observed and evaluated in different countries such as Denmark (Carla K 2007), the Netherlands (Ignatenko, van Schaik et al. 2008), the UK (Panate 2008), and China (Xiang and Ming 2011), the effect of the European ELV legislation has been assessed from innovation (Gerrard and Kandlikar 2007) and economic perspectives (Bellmann and Khare 2000). Moreover, the reuse and recycling weight rate proposed by EU directive is criticized and new measures for mass and energy have been proposed (Amini, Remmerswaal et al. 2007; Ignatenko, van Schaik et al. 2008).

There are a handful of studies with the objective of providing decision elements for ELV recycling network stakeholders, aiming for identification and representation of concrete measures and criteria. However, the financial and economic models for ELV recycling networks are at the macro level, or focus on only one activity of the network. To the authors' knowledge, there is no indexed publication on ELV glazing recycling.

In the fourth category, Duval (2007) developed a financial model to estimate the costs that would have to be borne if the company participated in the proposed recycling network. Boix (2012) proposed a flow optimization technique to achieve a global economic profit. Erol (2005) developed a methodology for the eco-design of reuse and recycling networks by multi-objective optimization. Maudet (2007) discussed the recycling integration issues in the supply chain. Finally, Williams (2007) proposed a recycling planning model for automotive shredders to make short-term tactical decisions.

Nonetheless, a sustainable recycling system requires environmental, institutional, financial, economic and social sustainability (Athanassiou and Zabaniotou 2008). The need for economic evaluation of different strategies in end of life (Gehin, Zwolinski et al. 2008) is essential, as well as evaluation of the environmental gain and loss of different strategies (Nahman 2011).

Concerning ELV glazing, besides the advantages of using glass cullet in glass making (already mentioned in the introduction), there are very few relevant papers. The most frequently cited causes for an absent ELV glazing recycling network in France and EU countries are the economic barriers (Gillot 2000; ADEME 2008; MEEDDM

2009). These barriers have been discussed at a macro-economic level, but none of the studies have adequately attempted to calculate the specific incremental costs and benefits of the whole network. Moreover, the technical possibilities, such as treatment of windshield in a glass treatment unit, and limitations, such as quality restrictions for cullet acceptance for different uses in such a network, have not been addressed.

In today's market conditions, where end-of-life design considerations are not a high priority for car manufacturers (Gerrard and Kandlikar 2007), the most effective way to develop a recycling network is to integrate the recycling policy into existing business and the market realities (Maxwell and van der Vorst 2003). The extension of producer responsibility for ELV recycling (Luttrupp and Johansson 2010; Xiang and Ming 2011) suggests that the study of ELV recycling network should be conducted in a consortium of recycling stakeholders including the car manufacturer.

For this study, we have investigated a future ELV glazing recycling network in France, and have built a conceptual value chain in which all the stakeholders of the recycling operation, including the dismantling stakeholder, collection and storage player, glass treatment player, glass production player (as of a potential buyer for the cullet) and car manufacturer. We interviewed at least one major player of all roles in order to obtain and verify previously extracted technical and economic information of the future ELV recycling network. References to these industrial partners however remain anonymous because of the confidentiality issues.

## **2. FORMULATION OF MODEL FOR ELV GLAZING**

### **2.1 Envisioned recycling network for ELV glazing in France**

The future ELV glazing recycling network is shown in fig.1. As mentioned earlier, there are five (5) main activities in the network: collection of ELVs; dismantling, collection and transportation of the dismantled glass; landfilling the shredding residual; storage; treatment of glass; and sale of the cullet produced.

Our model (fig.2) illustrates the different possible network configurations. ELV collection is a bin or storage area where the end users leave their cars. The ELVs are then distributed to one of the seven (7) dismantling units, denoted as  $d$  in fig.2, with different procedures of glazing removal, number one being for no glass dismantling. Depending on the removal process, the removed glazing has different qualities (from pure glass to glass containing metal and PVB) which, in turn, requires different storage and treatment conditions. Consequently, all these operational choices are interdependent.

The dismantled glazing is collected by the collection and transport players, and stored in one of four (4) storage centers, denoted as  $s$  in fig 2, according to the quality of glazing. The same player supplies the glazing to the relevant glass treatment unit, based on the quality of glazing and transport costs. For example, high quality glazing could be sent to a low quality treatment unit, because the transport cost of sending it to a high quality treatment unit is too high (e.g. due to the distance) and so the treatment unit does not ask for the glazing.

There are four main types of glass treatment units, denoted as  $r$  in fig. 2, which produce different cullet products. The cullet can have various product specifications, depending on the specific demand of the customer. In this study, we consider nine cullet products (categorized by size and quality), designated for four main markets, denoted as  $m$  in fig.2).



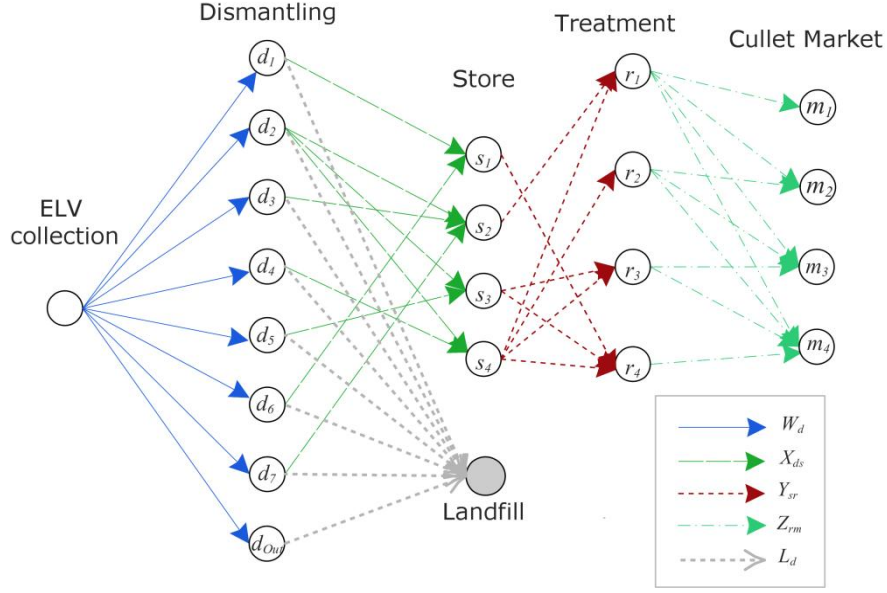


Figure 2. Future recycling network for ELV glazing in France, based on technical scheme at national level. Symbols are explained in nomenclature

The network structure, technical operation procedures, decision parameters and constraints are based on the ADEME reports, the EU ELV official reports, as well as the ground study and interviews of potential domestic and foreign industrial players of a future ELV glazing recycling in France. A detailed explanation of the data is given in Section 3.

## 2.2 Linear programming formulation

A linear programming model is proposed in this paper to obtain an optimal material flow in ELV glazing recycling network in France. The mathematical formulation of the model follows, while the detailed explanation of the parameters and constraints is included in Section 3.

### 2.2.1 Objective function

The objective is to maximize profit, which consists of income from selling the cullet in the market, minus the operating costs of each step as expressed in Equation 1.

$$\begin{aligned}
 \text{Max} \left\{ \left[ \sum_{m \in M} \sum_{r \in R} Z_{rm} P_m \right] \right. \\
 - \left[ \sum_{d \in D} W_d C_{Dd} + \sum_{d \in D} L_d C_{Ld} + \sum_{s \in S} \sum_{d \in D} X_{ds} C_{COLds} + \sum_{s \in S} \sum_{d \in D} X_{ds} C_{STOds} \right. \\
 \left. \left. + \sum_{r \in R} \sum_{s \in S} Y_{sr} C_{TRA_{sr}} + \sum_{r \in R} \sum_{s \in S} Z_{sr} C_{TRE_r} + W_{out} C_{Out} \right] \right\} \quad (1)
 \end{aligned}$$

Where  $W_d$ ,  $W_{out}$ ,  $X_{ds}$ ,  $L_d$ ,  $Y_{sr}$ , and  $Z_{rm}$  are the design variables of the model, the material flow between the network nodes,  $P_m$ ,  $C_{Dd}$ ,  $C_{Ld}$ ,  $C_{COLds}$ ,  $C_{STOds}$ ,  $C_{TRA_{sr}}$ ,  $C_{TRE_r}$ , and  $C_{Out}$  are unit profit and costs for each node, respectively, as listed in Nomenclature. The detail of material flows equations and cost calculations are presented in Appendix 1.

### 2.2.2 Constraints

The constraints are divided into three categories. The first category is the material flow conservation in each node. Equations 2-5 represent the flow conservations at ELV collection sites, dismantling unit, storage site, and recycling plant, respectively:

$$\forall d \in D; \sum_{d \in D} W_d + W_{Out} = W \quad \text{Flow conservation at ELV collection} \quad (2)$$

$$\forall d \in D; W_d F_d = \sum_{s \in S} X_{ds} x_{ds} \quad \text{Flow conservation at dismantling unit } d \quad (3)$$

$$\forall s \in S; \sum_{d \in D} X_{ds} F_s = \sum_{r \in R} Y_{sr} y_{sr} \quad \text{Flow conservation at storage site } s \quad (4)$$

$$\forall r \in R; \sum_{s \in S} Y_{sr} F_r = \sum_{m \in M} Z_{rm} z_{rm} \quad \text{Flow conservation at recycling plant } r \quad (5)$$

The second category is the capacity constraints for each node. Equations 6-8 represent the capacity limits of dismantling units, storage sites, recycling plants, respectively.

$$\forall d \in D; H_d \geq W_d \quad \text{Capacity limit of dismantling unit} \quad (6)$$

$$\forall s \in S; H_s \geq \sum_{d \in D} X_{ds} \quad \text{Capacity limit of storage site} \quad (7)$$

$$\forall r \in R; H_r \geq \sum_{s \in S} Y_{sr} \quad \text{Capacity limit of recycling plant} \quad (8)$$

Equations 9 and 10 give the market demand of cullet products and the capacity constraint for landfill sites, respectively.

$$\forall m \in M; H_m \geq \sum_{r \in R} Z_{rm} \quad \text{Demand constraint of market} \quad (9)$$

$$\forall d \in D; H_L \geq L_d \quad \text{Capacity constraint of landfill sites} \quad (10)$$

The third category of constraints imposes the flows to be positive or null, shown in equations 11-14:

$$\forall d \in D; W_d \geq 0 \quad (11)$$

$$\forall d \in D, s \in S; X_{ds} \geq 0 \quad (12)$$

$$\forall s \in S, r \in R; Y_{sr} \geq 0 \quad (13)$$

$$\forall r \in R, m \in M; Z_{rm} \geq 0 \quad (14)$$

### 3. ESTIMATION OF MODEL PARAMETERS IN FRANCE

Considering the fact that ELV glazing recycling currently does not exist in France, or in many European countries, the major obstacle of the network optimization is to obtain reliable data to estimate the parameter values. While units and activities necessary for glazing recycling exist, gathering conditional information pertaining to the addition of glazing flow would cause difficulties in estimation, rendering the data uncertain. For the purposes of this study, the information has been extracted from official reports of EU (Fergusson 2007), ADEME (ADEME 2006; ADEME 2007; ADEME 2008), Glass for Europe (Glass 2009), and interviews with interested industrial partners in a predictive model of glazing recycling network. Moreover, two experiments were conducted at an industrial site, first dismantling glazing from ELV to estimate operation costs, and second inserting the glazing material into a laminated glass treatment site to examine the quality of cullet produced and

estimate its treatment cost. The uncertainty of data however, remains in economies of scale. The estimation of the model parameters of the ELV glazing recycling network at each step is discussed below.

### 3.1 Dismantling of glazing and landfill

ELV glazing represents 2.9 % of ELV weight, so if complete dismantling and recycling were processed, it could significantly contribute to the targeted mass rate. Today's recycling and recovery rate in France is estimated at 85% (ADEME 2008): the glazing recycling and recovery would therefore contribute a little less than a third of the necessary effort to reach the 95% target.

Automotive glazing consists of windshield (approximately 17kg per vehicle, containing Polyvinyl butyral (PVB) layers), back window (approximately 15kg, containing metal wire), and side windows (approximately 9kg, glass only), these data being for a contemporary car manufactured since 2009. These figures may well increase by 5-10% in the future, due to the current practice of increasing the glazing surface (Saint-Gobain 2012).

There are 1 565 dismantling units in France with a normal geographical distribution all over the country (ADEME 2008). Dismantling activity uses government subsidy because of the difficulty in self-financing. The latest evaluation of ADEME reported that the EU ELV rate of reuse and recycling had not been reached, and emphasized the fact that almost all dismantlers did not dismantle the maximum possible out of an ELV (ADEME 2006). The main reason does not come from within the dismantling firm, but is due to the lack of a collection system. ADEME estimated the ELV flow of 798 ELVs on average per year per dismantling unit.

Today, the main barriers against glazing removal are: first, a lack of an efficient glass collection system, dismantling the glazing causes an extra cost, and needs enough room for storage until casual collection. Second, leaving materials on ELV causes no limit from the buyer (shredder) and since the trade is based on shell weight, there is no financial motivation to remove parts (including glazing) unless the separate selling income for the dismantler is higher than the price (40-45 €/ton (ADEME 2008)) and could compensate the removal operation cost.

Glazing removal is a manual procedure, needing no particular technology or device (except perhaps a bloke with a hammer), and with no extra energy consumption. Thus the dismantling procedure can be parameterized using the dismantling time as the main variable. Accordingly the cost variation of glazing dismantling procedures can be considered the same as the time needed to perform a removal procedure. Depending on the procedure (for example side windows, or all glazing) time and consequently cost vary.

From the ELV glazing dismantling experiment realized by a professional dismantling unit, the following data are extracted: The reference time ( $\mu_d$ ) and the cost ( $C_{D_d}$ ) for a variety of dismantling procedures were obtained as shown in Table 2. In addition, two parameters were found to be necessary for modeling the glazing material flow over a dismantling unit: reference weight per ELV ( $\rho_d$ ) and yield ( $\tau_d$ ), which is the average weight of dismantled pieces divided by total weight. For example in practice it is possible to remove on average 70% of a windshield, 30% remaining on the frame. The flow and cost calculation equations are presented in Appendix 1.

The quality of dismantled glazing depends on the procedure, so it is important to prevent mixing inventories by separating the storage sites. There are four storage types possible for glass inventories, shown in Table 2. Clearly, an inventory containing windshields should not be mixed and stored together with an inventory of side windows only, because windshields necessarily need laminated glass treatment (which is more costly than non-laminated glass treatment). Mixing two inventories decreases quality and may lead to extra costs. Thus, there is an allocation matrix indicating what connections are permitted between each dismantling unit  $d$  and store site  $s$ , expressed by the form  $x_{ds}$  shown in Table 2 in a bold frame.

Table 2. Model parameters for dismantling procedure/unit

	<i>Dismantling procedure</i>	<i>Yield</i> ( $\tau$ )	$\rho$ (kg)	<i>Time indicator</i>	<i>Storage unit</i>			
					$s_1$	$s_2$	$s_3$	$s_4$
					Mixed glazing	Windshield + sides	Back + sides	Side only
$d_1$	Mix of all glazing	80%	42	$\mu_1=1$	1	0	0	0
$d_2$	All glazing separately	80%	42	$\mu_2=1.2$	0	1	1	1
$d_3$	Only windshield	70%	28	$\mu_3=0.8$	0	1	0	0
$d_4$	Only side windows	95%	4	$\mu_4=0.6$	0	0	0	1

$d_5$	Back and side windows	70%	12	$\mu_5=0.7$	0	0	1	0
$d_6$	Back and windshield	80%	38	$\mu_6=0.8$	1	0	0	0
$d_7$	Side and windshield	72%	32	$\mu_7=0.9$	0	1	0	0

### 3.4 Collection and transportation

Collection and transportation of recyclable material from inventories to store units and then to treatment plants is an increasing activity in France. A study was carried out to estimate the optimum collection and transportation costs for ELV glazing logistics at national level in France (ISEL 2011). The study reported that between 96 and 142 collection centers are capable of storing recyclable glass, which are far greater in capacity than the required storage for glasses, and therefore they do not impose constraints. However, the charging and discharging of the stored glasses require resources, and costs on average 7.32 € for a 10-ton bin.

There are two possibilities for collecting ELV glazing from dismantling units: to organize a logistical system and dedicated truck to collect only glazing, or to share the glazing collection with other material collection from dismantling units.

The second solution seems much more interesting because of potential cost savings in transportation, less CO<sub>2</sub> emission, and more frequent collection. However, it is very difficult to find an estimate for this alternative, due to the lack of data. The cost of the first option was estimated at 47.36 €/ton on average, which can be reduced to 38.30 €/ton with optimized logistics. In a recent interview with an industrial professional, it was estimated that sharing the glazing with other dismantled material could decrease the cost to 20 €/ton on average. We used this lower estimation for the storage sites for side windows only, because of the relative simplicity of collection, and used 38.3 €/ton for other storage sites.

The stored glazing will be transported to a glass treatment plant. There are four main types of glass treatment process, as shown in Table 3. The allocation of a storage unit to a treatment plant depends on both the quality of the stored glazing and the requirement of the treatment processes. Clearly, a non-laminated treatment plant does not process windshields, and as the mixed glazing is not good enough to be processed for the glass industry, it will be used as a substitution material. Thus, an allocation matrix indicating connections between each storage unit  $s$  and treatment plant  $r$ , expressed by parameter  $y_{sr}$ , is shown in Table 3 inside a bold frame.

The transportation cost per unit weight is based on the average distance between a storage site and a treatment plant. Simple treatment plants (e.g. shredding and metal separation) and container glass treatment units are homogeneously distributed across France (Verre-avenir 2011), indicating a low average distance. However, there are only two recycling plants for non-laminated glass and three for dual (laminated and non-laminated) recycling in France, and only one dual plant in Belgium, so average distance is high. The logistics study proposed an average cost of 25.58 €/ton for optimal transport from a storage site to flat glass treatment units (including the one in Belgium). For simple treatment plants, of the average cost is estimated as 15 €/ton for significantly lower average distance to these plants. Moreover, only the plant in Belgium is capable of producing good quality cullet from ELV glazing, by using modern facilities. To take this difference into account, we use four different values of transport cost, corresponding to the quality character of the treatment process, as shown in Table 3.

Table 3. Model parameters for collection, store and transport

		Glass treatment processes				
		$r_1$	$r_2$	$r_3$	$r_4$	
	Collection cost (€/ton)	Laminated flat glass	Non laminated flat glass	Container glass	Simple treatment	
Glass store types	$s_1$	38	0	0	1	1
	$s_2$	38	1	0	0	0
	$s_3$	38	0	0	1	1
	$s_4$	30	1	1	1	1
	Transportation cost (€/ton)		30	25.58	20	15

### 3.5 Glass treatment

Glass treatment consists in a series of shredding, sieving, separation and purification to transform the incoming glass to a reusable secondary raw material called cullet. A treatment unit can produce more than 20 different cullet products in a variety of sizes (0-5, 5-10 mm and 0-10mm) and qualities (good, average, low).

Each treatment process is characterized by yield and process costs, and has a technical constraint on the mass equilibrium between two cullet products. The mass transformation of each process is calculated from the process yield. Equations are presented in Appendix 1.

Cullet products with different size and quality will be sold in four main types of market. The allocation matrix ( $z_{rm}$ ) between treatment processes to markets is shown in a bold frame in Table 4. The estimation of process cost is based on (Glass 2009) and on interviews with glass cycling plant managers and flat glass production engineers.

Various reports and studies expressed the increasing need for cullet from the glass industry (Verre-avenir 2011), particularly for high quality cullet (Remade-Scotland 2003) and also for substitution uses (Reindl 2003). Good quality cullet which can be used for glass production has the highest price, close to the raw material price. While the cullet price in the market follows the supply and demand trend, the cullet production in most European countries lags far behind demand, due to undeveloped recycling networks. Thus, it is possible for the optimization model to consider market demand as infinite. The market prices of the cullet with different size and quality were estimated from market research and industrial interviews.

Table 4. Model parameters for glass treatment and cullet production

				Cullet markets				
				$m_1$	$m_2$	$m_3$	$m_4$	
Glass treatment processes	Product quality	Process cost €/ton	Cullet size (mm)	Flat glass production n	Container glass production n	Glass whole productio	Substituti on market	
	$r_1$	Good	22	0-5	0	1	1	1
				5-10	1	1	0	0
	$r_2$	Good	20	0-5	0	1	1	1
				5-10	0	1	0	1
	$r_3$	Average	20	0-5	0	0	1	1
				5-10	0	0	1	1
	$r_4$	Low	15	0-10	0	0	0	1
	Market Price €/ton				55	45	21.5	17

#### 4. RESULTS AND DISCUSSION

Based on the parameters and data described, a network and material optimization was performed using the Xpress solver. We used the real number of 1.5 million of ELVs being received by certified dismantling units in France per year. Beside the landfill cost of 70 €/ton (the cost of disposing of the banal waste for shredding residual and glass waste), other costs and prices are taken from the previous section.

The optimization model chose not to allocate the ELVs to any glazing dismantling procedure. In other words, the profit of the recycling network is less than the cost of taking the whole glazing on ELV shell to landfill, equal to 2.87 €/ELV, or 4.3 M€ in total. This result provides an economic explanation which uses a bit of mathematics for the non-existence of a glazing recycling chain in France, albeit from the whole network point of view.

Changing the values of variables in the model unbalances the cost-benefit equilibrium of the network, so the optimization solver proposes new network topology (different operational alternatives) and material flows. This changing situation however is inevitable in the near future, because of market evolution and politico-economic variables. In a recent publication we described the dynamics of the influence between variables, and pointed out the changing trends (Farel, Yannou et al. 2012). In the current study we select three key variables identified in

the former publication and perform a sensibility analysis to investigate the effect of each variable on the optimization results. These three variables are: landfill cost, the penalty amount in case of non-attainment of the 95% rate, and cullet price in the market. Below we describe the general trend of each variable, propose a range for variation of the variable, and illustrate the effect of variable evolution (keeping other parameters unchanged) on the optimal material flow of the glazing recycling network.

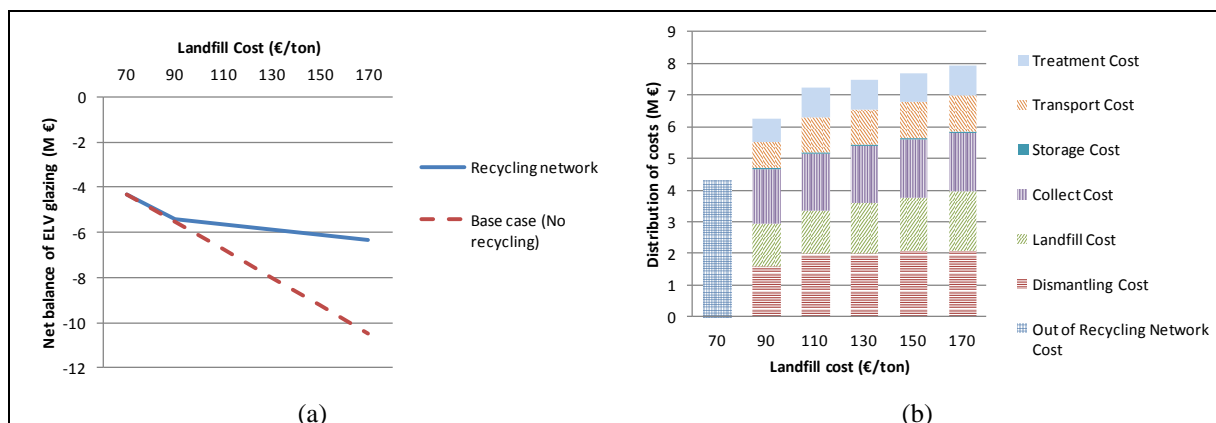
#### 4.1 Landfill cost

Within the boundary of this study, the landfill cost was considered as the waste disposal charge; its value was obtained from formal reports and industrial interviews. However, the external (environmental and social) costs of landfill (e.g. emissions to air, soil and water) are difficult to quantify in monetary terms, and are therefore not generally reflected in waste disposal charges or taken into account in decision-making regarding waste management options (Nahman 2011). Taking into account the external costs in monetary terms would lead to a higher amount, favouring the policy of increasing landfill cost (Couth, Davies et al. 2003). In France, ADEME is predicting the increase of waste disposal taxes in the near future (DiCostanzo 2008).

The increase in landfill cost is a motivating factor for industrial players to prefer the dismantling activity and remove as many parts and material as possible, in order to decrease final shredding residual, and consequently the landfill cost. In order to investigate the effect of an increase in landfill cost on the glazing recycling network, a series of optimizations is performed varying the amount of landfill cost from 70 to 170 €/t, with increments of 20 €, as shown in Fig. 3.

As Fig. 3(a) shows, a slight increase in landfill cost (less than 30%) makes the recycling activity less costly than no glazing recycling. While the progressive increase of landfill cost linearly increases the cost of not recycling, the glazing network can significantly save costs and reduce expenditure.

Fig. 3(b) shows the cost distribution of network activity costs, which are not very sensitive to the increase in landfill costs. The optimal solution at the cost of 90 €/ton is to allocate 80% of ELV to back and windshield dismantling, and the rest to dismantling all glazing separately. However, the proportion inverses at higher landfill costs (Fig. 3(c)). The main reason of this allocation is the motivation to remove the highest amount of glazing weight possible from the glazing, while the back windows are contaminated (because of heating wire) and are not adequate for good quality cullet production. As Fig. 3(d) shows, the dismantled glazing is allocated to all four store types with no big difference. Consequently, the glazing inventory is almost equally allocated to the best and the worst treatment quality plants (see Fig. 3(e)). The two obtained cullet types are also equally sold on the two markets of flat glass and substitution market (Fig. 3(f)).



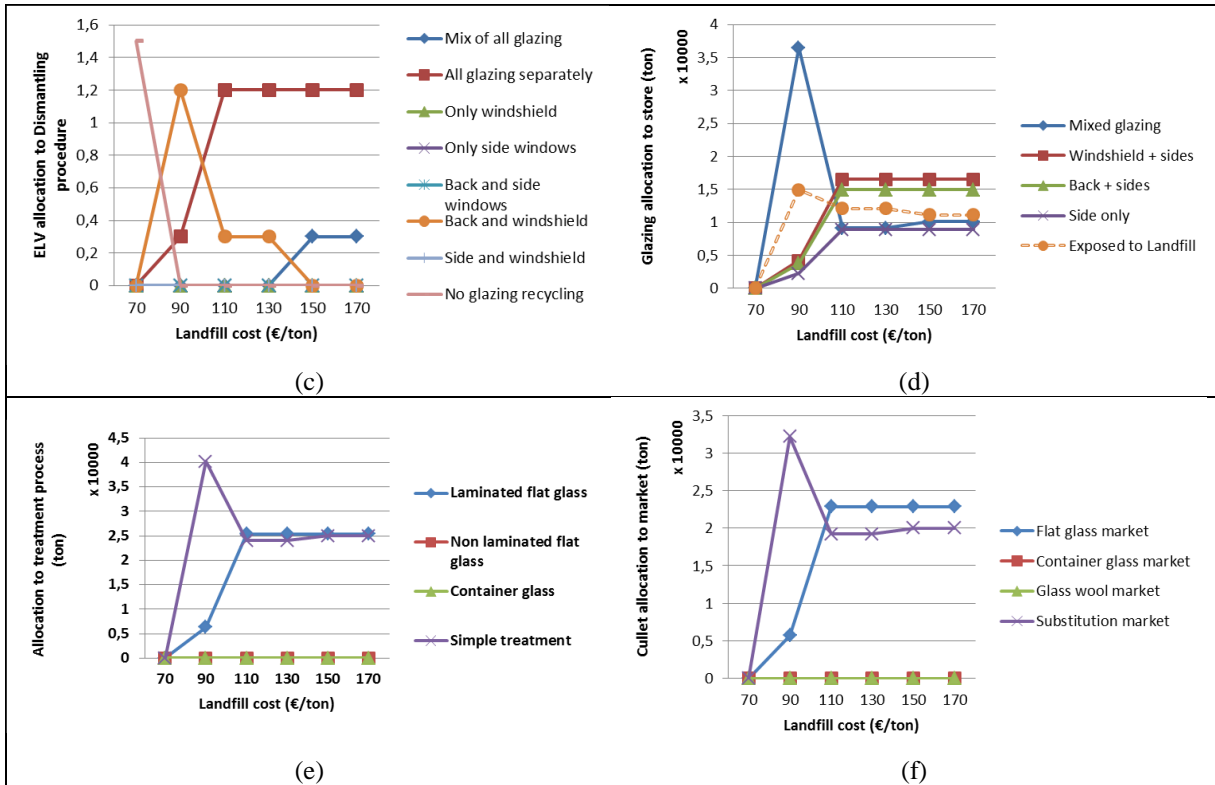


Figure 3. Effect of landfill cost on glazing recycling network

In summary, if landfill cost increases slightly (up to 87 €/t), the optimum scenario for the network is to focus on two markets: substitution with 85% and flat glass with 15%. For the values higher than 95 €/t, the model proposes to change the objective to substitution with 46% and flat glass with 54%. If the ELV glazing is designated for the substitution market, then the best dismantling procedure is to remove windshields and back windows, store in mixed units and use simple treatment (Fig. 4). For the flat glass market, the optimum dismantling procedure is to dismantle all the glazing and keep them separately, and send to separate storage units.

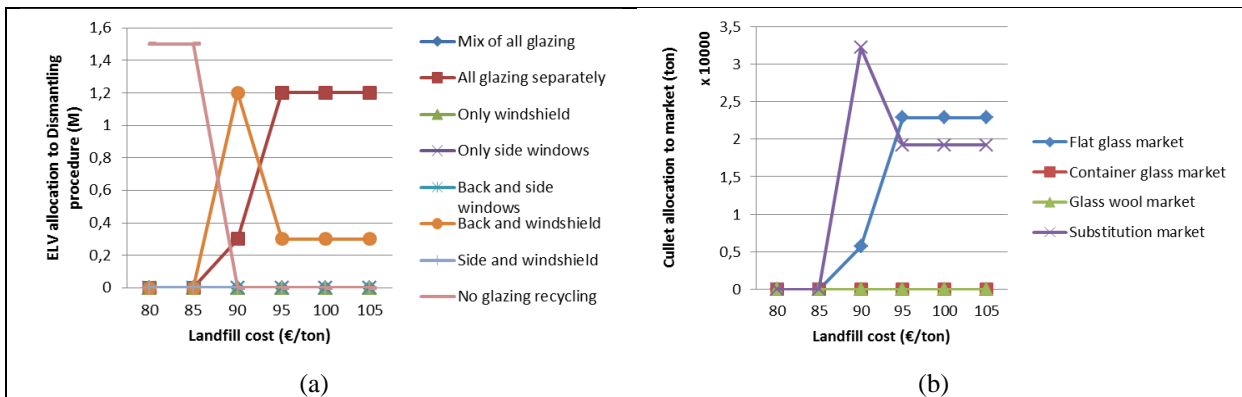


Figure 4. Zoom on critical value for the effect of landfill cost on ELV glazing recycling network

Accordingly, three scenarios can be imagined for the ELV glazing network.

#### Scenario 1: Small increase in landfill cost from 87 €/ton to 95€/ton

In this scenario, in order to maximize the network profit, the optimization model recommends to prioritize the dismantling of windshield and back window (80%), store in mixed storage units, and assign the inventory to simple treatment in order to produce low quality cullet intended for the substitution market. Figure 5 illustrates the network topology and the flow attribution to each operation phase.

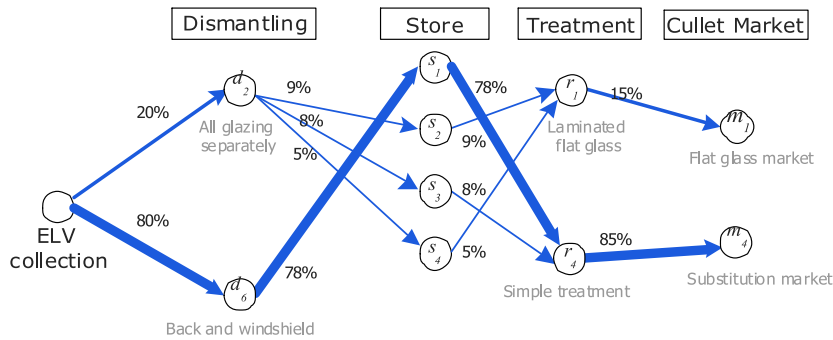


Figure 5. Recycling network optimum in Scenario 1

**Scenario 2: Increase in landfill cost from 95 €/ton to 150 €/ton**

In this scenario, the model proposes the dismantling of all glazing (80%) with separate storage. The reason is to maximize two inventories: first, good quality glazing with laminated glass treatment, intended for the flat glass market. Second, mixed glazing inventory with simple treatment intended for the substitution market (fig.6).

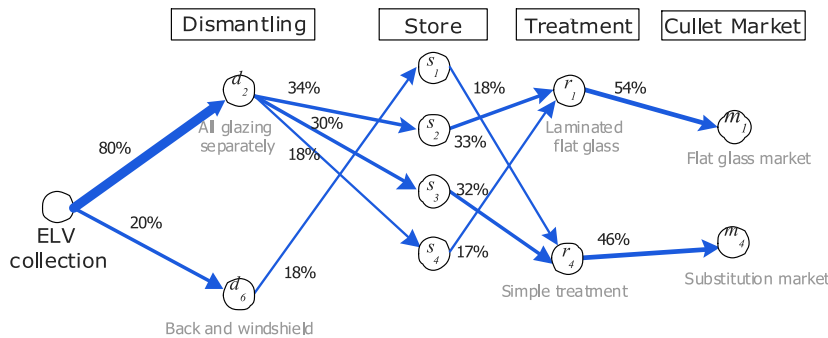


Fig 6. Recycling network optimum in Scenario 2

**Scenario 3: High increase in landfill cost, more than 150 €/ton**

In this scenario, the model chooses the dismantling of all glazing, storing them separately (80%). The increase of landfill costs from scenario 2 to 3 explains why the model allocates the remaining 20% to mix glazing instead of back and windshield as in scenario 2. The optimum topology and flow of the network is shown in Fig. 7, with 53% of cullet intended for the flat glass market and the remaining for the substitution market.

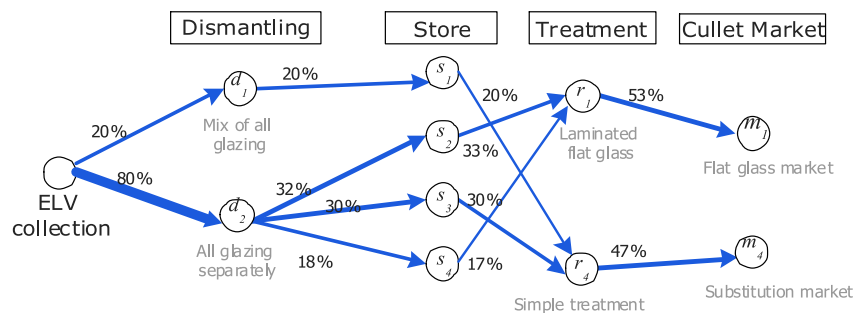


Figure 7. Recycling network optimum in Scenario 3

**4.2 Penalty effect**

The EU ELV directive will impose a penalty on car manufacturers in 2015 if the target rate of 95% of reuse and recycling cannot be met. The amount of this penalty is yet to be decided, but an estimation of a rational range



can be made. By trial and error, an estimation made on the critical value of the penalty, and a range for this value is proposed. As Fig. 8(a) shows, even a very small penalty (0.5 € or more) makes the glazing recycling more economical than not recycling. The cost distribution of activities is not sensitive to the penalty increase (Fig. 8(b)), and the optimum solution is to dismantle windshields only or with side windows (80% and 20%), and to store in relevant storage sites (Fig. 8 (c and d)). The glazing inventory is then sent to laminated glass treatment plants, to produce good cullet to be sold in the flat glass production market (Fig. 8(e and f)).

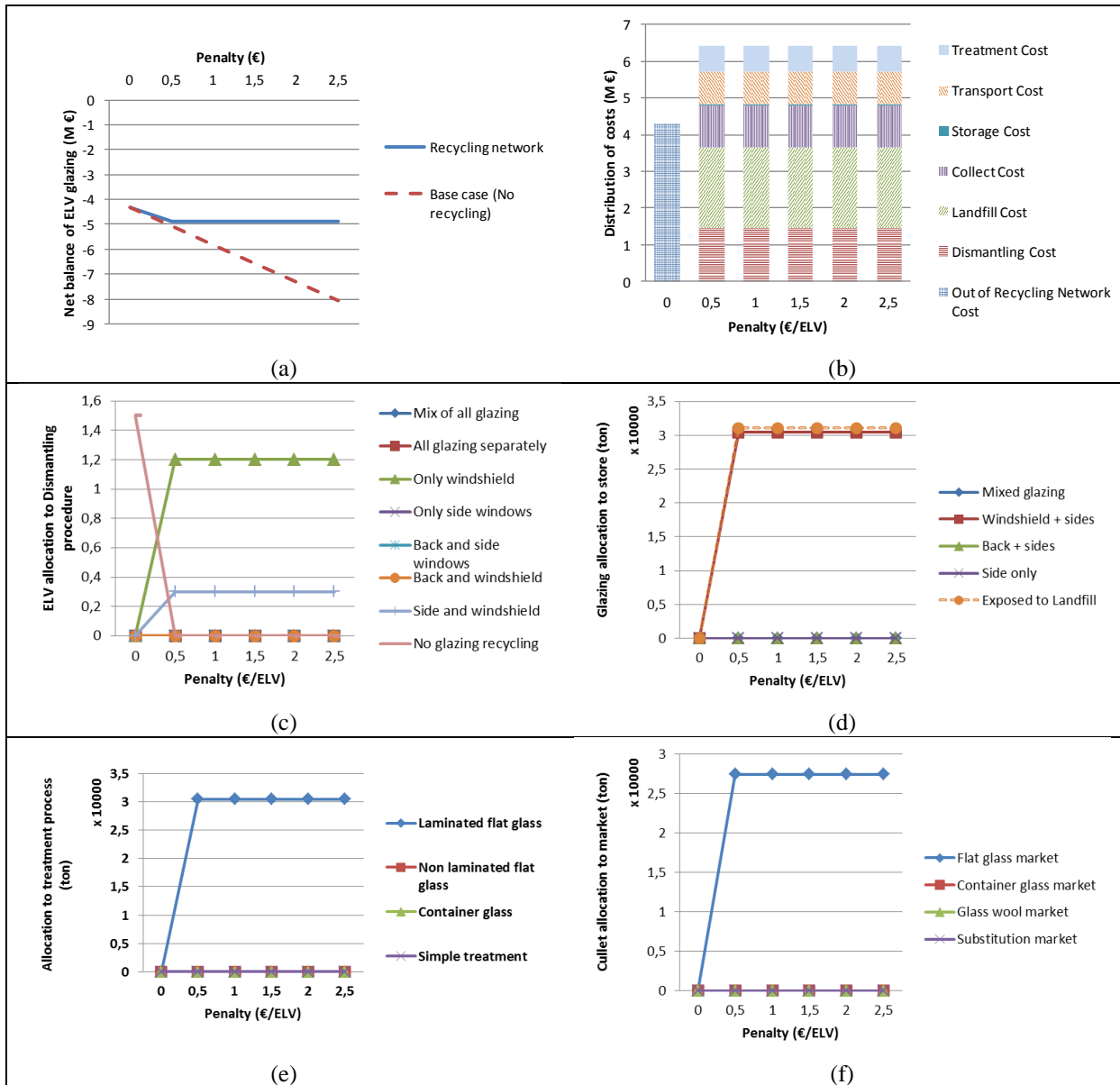


Figure 8. Penalty effect on glazing recycling network

#### Scenario 4: Application of penalty in case of non-achievement of recycling target rate

Accordingly, in the case of setting a penalty for not recycling, for any value more than 0.5 €/ELV, there is one optimum topology and flow attribution for the network, shown in Fig. 9. In this scenario, the model chooses the dismantling of windshields and high quality treatment in order to send the cullet to the flat glass market.

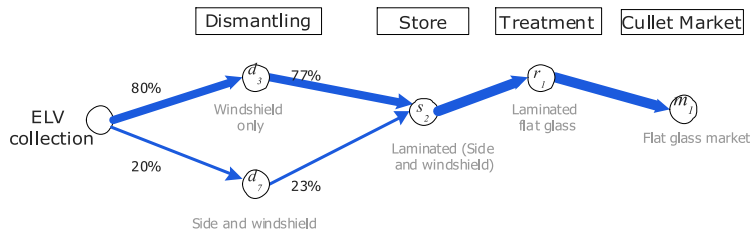


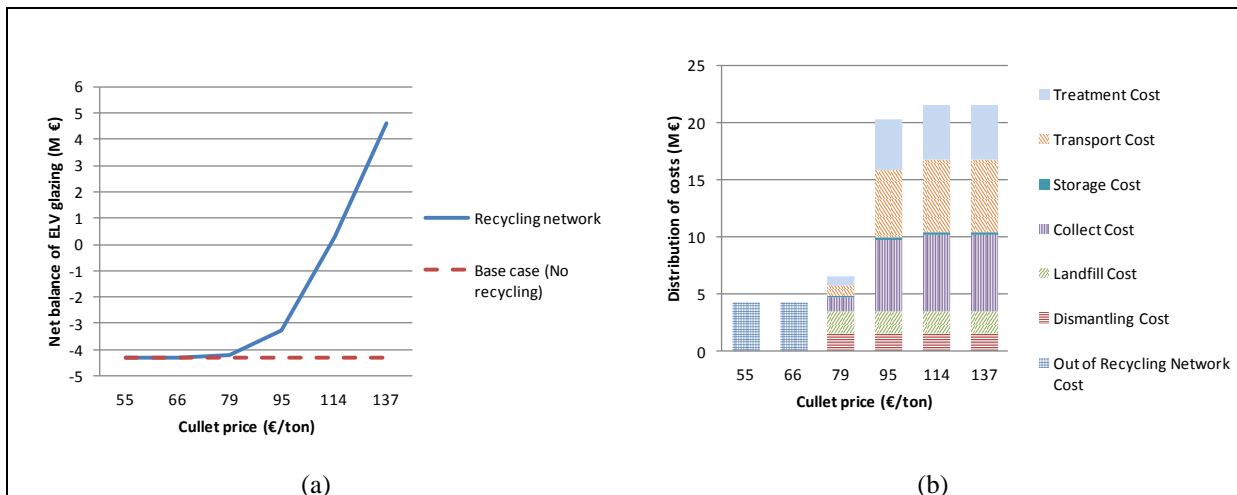
Figure 9. Recycling network optimum in Scenario 4

### 4.3 Cullet price increase

The increasing demand for cullet, and particularly for good quality cullet, will increase the cullet price in the market. For this scenario, the increase rate is not necessarily the same for all cullet. Thus, we estimated a series of increases for the price of cullet in four markets. A series of six price increases is shown in Appendix 2. Results of network optimization for the given data for the first market (Appendix 2, Table) are presented in Fig. 10 (a) to (f).

When cullet prices reach a certain value between 66 and 79 €/ton, glazing recycling becomes less costly than leaving the glazing on ELV. At a higher price, around 114 €/ton, the revenue from cullet sold in the market compensates the operation and makes the recycling network self-financing. At higher cullet prices such as 137 €/ton, almost 2.5 times as the initial value, the network becomes significantly profitable as shown in Fig. 10(a).

Fig. 10(b) shows the cost distribution for the component activities. When recycling becomes financially viable and increases in rate, the costs of collection, transport and treatment increase. The reason lies behind the choice of dismantling procedure, as shown by Fig. 10(c). The optimized solutions are side windows for 80% of ELV flow, and windshields for the rest. This choice implies almost the same proportion for storage types: 180 K tons of sides only, against 33.5 K tons of windshields and sides (fig. 10(d)). Almost all this glazing inventory, which is of the best quality, is sent to laminated glass treatment, because of higher process quality and thus the higher cullet price, and from a certain value (between 95 and 114) it is economically viable to allocate a flow to non-laminated glass treatment (fig. 10(e)). These two cullet products are sold in the flat glass production and container glass production industries, with the same proportion as shown in Fig. 10(f).



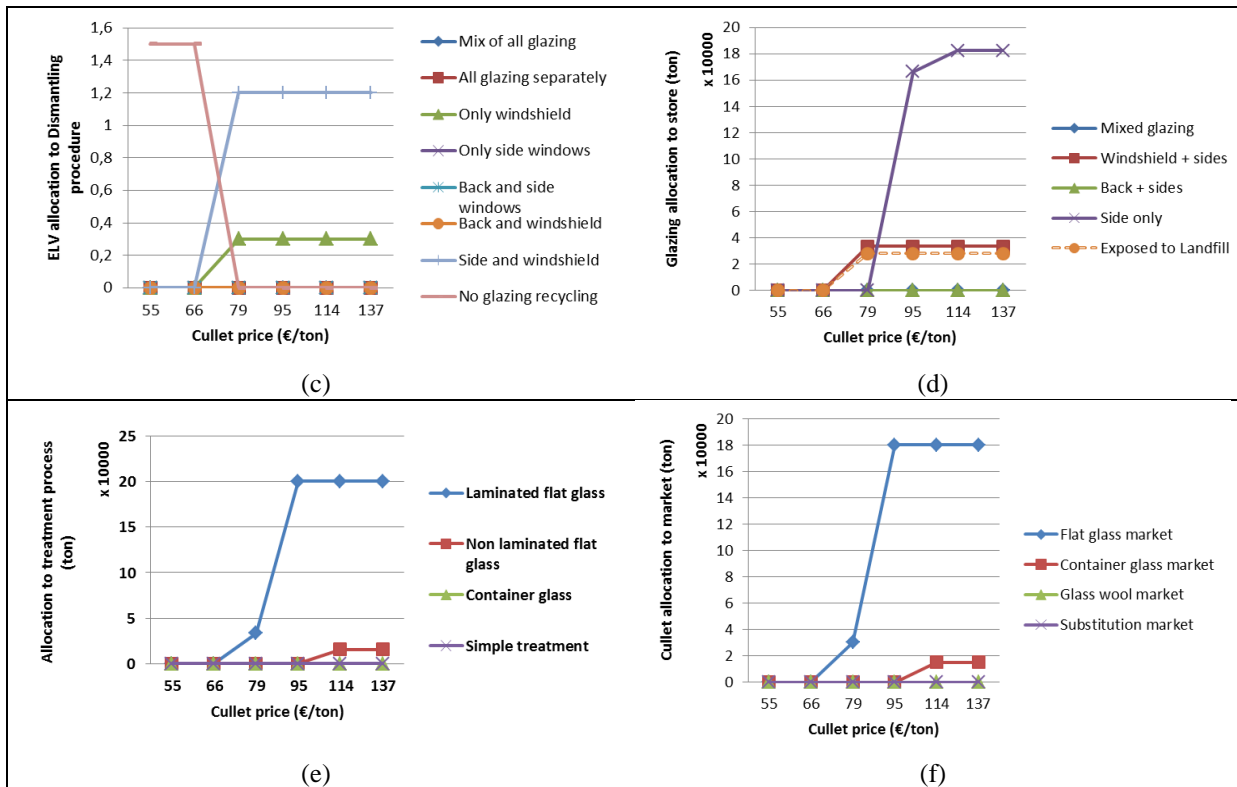


Figure 10. Cullet product increase effect on the ELV glazing recycling network

Therefore, there are two critical values for cullet price which influence network behavior, as the following section will explain.

### Scenario 5: Small increase in cullet price from 66 to 79 €/ton

In this scenario, the model chooses side window and windshield dismantling, and allocates the whole inventory for laminated glass treatment and therefore for the flat glass market, as shown in Fig.11.

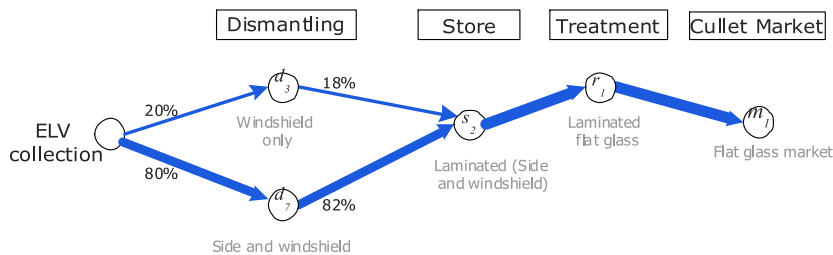


Fig 11. Recycling network optimum in Scenario 5

### Scenario 6: Cullet price increase from 79 to 95 €/ton

In this scenario, the model proposes to separate the side window and windshield before sending them to the storage site, because the collection of side windows is less expensive. The main recommendation remains the same: laminated flat glass treatment to obtain a good quality cullet intended for the flat glass market.

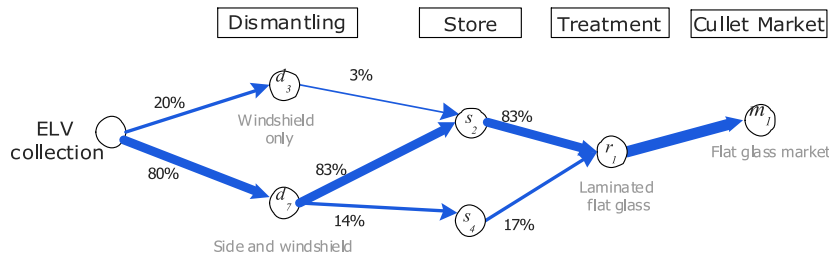


Figure 12. Recycling network optimum in Scenario 6

**Scenario 7: Cullet price greater than 144 €/ton**

In this scenario, the model allocates a small part of the flow (8%) to the container glass market, because of the high prices of all cullet types. For this, the model proposes a small flow allocation to non-laminated glass treatment ( $r_2$ ), as shown in Fig.13.

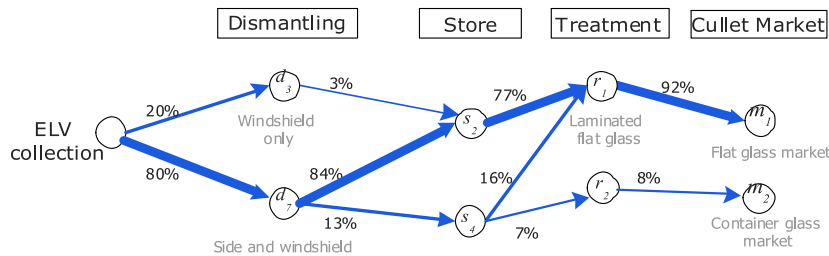


Fig 13. Recycling network optimum in Scenario 7

Table 5. Summary of scenarios result of different values for landfill cost, cullet price, and obligation or not of the penalty

		Landfill Cost (€/t)			
		70	87-95	95-150	>150
Cullet price (€/t)	55	Penalty	No Penalty		
		S4	Base case	S1	S2
	66-78		S5		
	79-95		S6		
>144		S7			

**4.4 How to structure the future network?**

The results presented above (summarized in Table 5 by scenarios) demonstrate the sensitivity of the network to each of the key variables, and propose the optimum topology and material flow of the network using estimated values for those variables. Hence, an open question emerges for discussion: how can the stakeholders of the recycling network use the information provided to make decisions for network organization and operational alternatives? In order to answer this question, we performed a factorial Design Of Experiment (DOE) plan to demonstrate the glazing recycling net balance. Two factors of the DOE are landfill cost and cullet price. The range of the landfill cost is from 80 to 205, which by 5 unit step provides 25 points. The range of cullet price is from 55 to 200, which with the same 5 unit step provides 30 points. Thus there are possible 750 combinations for net balance optimization. The result is demonstrated in a 3D plot, shown in Figure 14. From this representation it is understandable that the recycling network economic balance is rather carried by the change in cullet price. The increase of cullet price significantly decreases the recycling cost and brings it to the breakpoint.

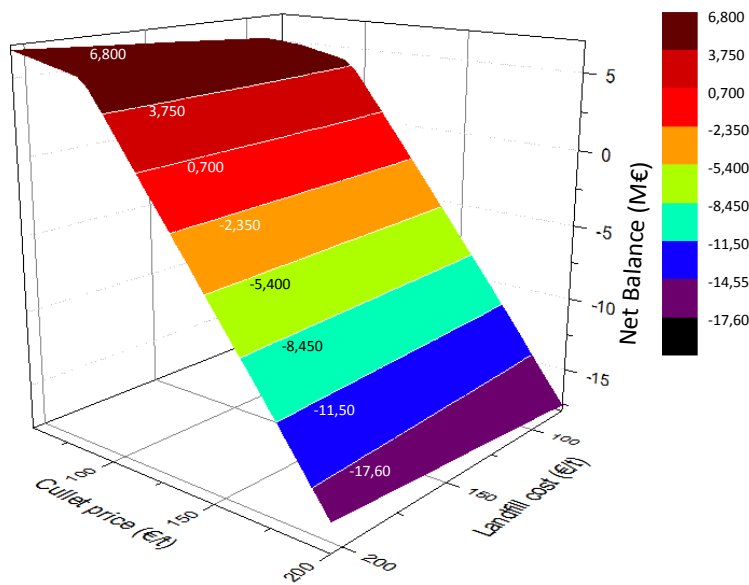


Figure 14 – Recycling network net balance as a function of cullet price and landfill cost

The glazing recycling network topography is indicated by the choice of alternatives in each step. In Fig 15, all seven aforementioned scenarios are shown with the optimum allocation of material flow in three operation steps of recycling: market attribution (Fig. 15 (a)), the storage site and relevant collection task (Fig. 15(b)), and dismantling (Fig. 15(c)). The glass treatment step appeared exactly the same figure as the market attribution, so it is represented on the same figure. Scenarios 1 to 3 are respectively low, average, and high increase in landfill cost. Scenario 4 is the application of a penalty, and finally scenarios 5 to 7 are respectively the low, average, and high increase in cullet price in the market. While no information can indicate which of low, average or high increases are the most probable in the future, we incorporate a cross variation to represent the most probable situation of the glazing recycling network in the future. The objective is to find out what topography of the network is the most sustainable in different scenarios.

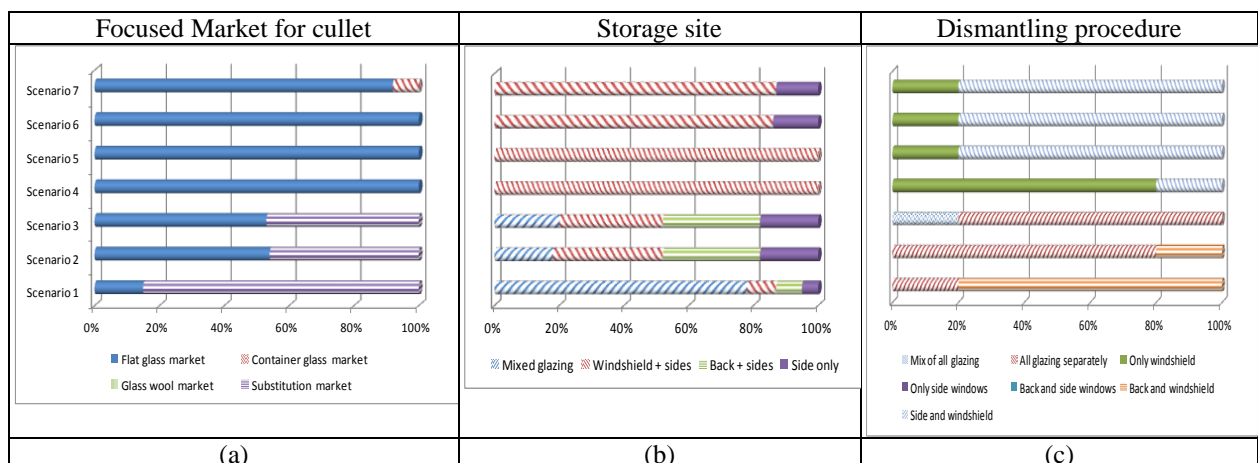


Figure 15. Future scenarios for ELV glazing recycling network in different network operation steps

**What is the best market for ELV glazing?**

As Fig. 15 (a) shows, the flat glass market is the recommended choice in case of penalty and cullet price increases. Although a low increase of landfill cost favors the substitution market, for the higher value of the landfill cost the attribution of cullet to the flat glass market increases significantly. Nonetheless, the best practice for the most probable situation is to focus on good quality cullet production resulting from laminated-glass treatment, for sale in the flat glass production market. Figure 16 shows the optimum allocation of cullet to different markets, with variation of both cullet price and landfill cost variables.

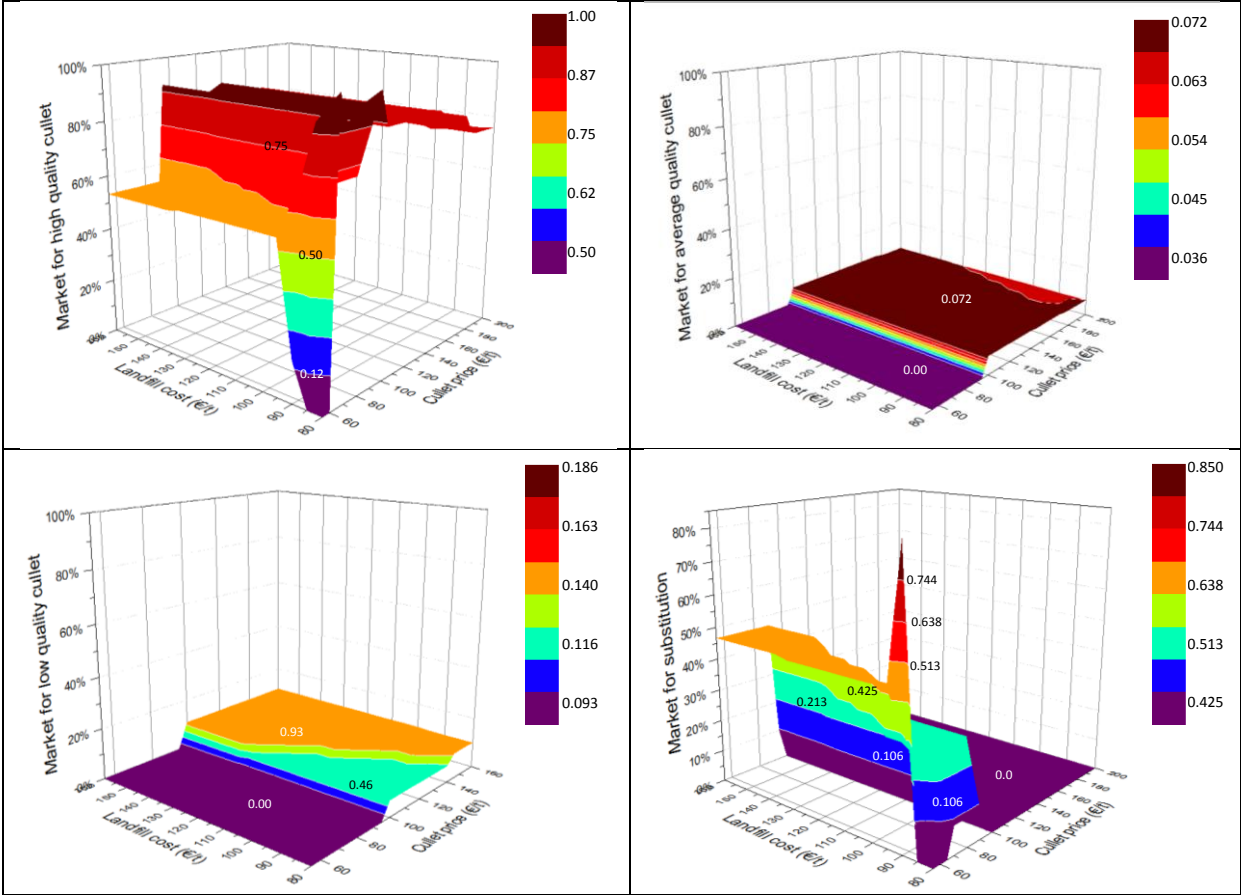


Figure 16 - Optimum market allocation for different cullet qualities

**What storage site is needed for ELV glazing collection?**

Although the windshield + sides store type is favored by cullet price and penalty scenarios, the landfill scenarios recommend an “all types” storage, except for a low increase in landfill cost in which case mixed storage is highly favored. In this regard it is difficult to identify a best practice for the most probable situation; nonetheless the combination of windshield + side and side only storage types are recommended, because of the high percentage in scenario 4 to 7, and the rational maximum share in scenario 2 and 3.

**What is the best glazing dismantling procedure?**

As Fig. 15 (c) shows, the network optimum is not the same in different scenarios. While an increase in landfill cost favors the dismantling of all glazing separately, the penalty and cullet price scenarios propose a combination of only windshield, and side windows and windshield dismantling. In this regard it is not possible to recommend a best practice for the most probable situation. However, looking at the dismantling alternatives leads us to recommend the dismantling of all glazing and with separate storage, for two reasons. First, this procedure is convenient for the two other alternatives with minimum modification. Second, since the best practices for other steps are in favor of separate storage and flat glass market, this procedure ensures the required quality for the following recycling operation.

## 5. CONCLUSION

ELV glazing recycling will become a legal requirement in France and in all EU countries in the near future. Car manufacturers are very concerned about the structure, performance, and cost-benefit balance of the future network. The possibilities and alternatives for each step of the glazing recycling must be studied carefully. General influencing variables such as environmental tax and market price increase could significantly impact the economic performance of the network. This paper proposes an optimization model with the objective function of maximizing the whole network profit. We use a linear programming technique to solve the mathematical model and determine the optimal network topology and material flow. The technical and economic data are extracted from industrial interviews and public and government reports in France.

The results of this study demonstrate three key points: First, in spite of the current non-economic benefit of the ELV glazing recycling, the added costs and potential income of establishing a recycling network as it is currently proposed and under suggested conditions, would result in a saving costs and making profit for the whole network considering probable evolutions in the near future. Second, the sensitivity analysis of the network economic performance under a value series of three key variables shows the influence of those variables on the network optimization both in topology and flow rate. Third, although the scenarios are simplified representations of the future evolution that would occur in ELV glazing recycling, the magnitude of the costs and benefits indicates the importance of those evolutions and provides a comparison between decision alternatives for stakeholders.

Today, the ELV glazing recycling does not seem to be economically viable. The current values represent a recycling cost which is greater than leaving the glazing to shredding and taking it to landfill. However, probable future economic evolutions contradict the present situation, and the increases in market demand for cullet or landfill tax make glazing recycling less costly, or even a profitable activity. The application of an estimated penalty as a cost to the network shows that, establishing the recycling network is more profitable for the car manufacturer. Last but not least, the proposed network optimization can demonstrate the impacts of scenarios on the environmental variables, such as CO<sub>2</sub> emission and waste production. While the carbon footprint calculation required a detailed LCA and was practically impossible because of lack of data, the amount of glazing taken to landfill in each scenario was calculated and shown in diagram (d) of Fig. (3, 8 and 10). In this regard, the increase in landfill cost gradually decreases the total amount of landfill waste, 10-15 k ton against 30k ton for other scenarios.

The impact of this study and the findings on the project stake holders was considerable. First, it provided a quantitative estimation of the impact of future changes on the net balance of ELV glazing recycling. Second, it was communicated to the public state decision maker to give them a realistic picture of the present techno-economic situation and the ideal net balance of a future recycling network at national level. Third, all stakeholders are provided with a configurable model and a traceable data set, in order to give them the possibility of simulation and optimization with new information, and estimate the net balance of ELV glazing recycling.

The optimization proposed in this paper was limited to net economic balance. Nonetheless, creating a recycling network brings many environmental benefits, such as decreasing the waste material taken to landfill, and decreasing CO<sub>2</sub> emission in result of less energy consumption. A forthcoming study will integrate environmental parameters into the cost and benefit model. Moreover, the optimization techniques can be extended to multi-objective (for example maximum income with minimum CO<sub>2</sub> emission) and deployed for individual stake holders.

## APPENDIX 1

### 1 Material flow

$$L_d = W_d(\rho - \rho_d \cdot \tau_d)$$

$$\bar{L}_d = W_{out} \cdot \rho + \sum_{d \in D} L_d$$

$$X_{ds} = W_d \cdot \rho_d \cdot \tau_d$$

$$Y_{sr} = \sum_{d \in D} X_{ds}$$

$$Z_{rm} = \sum_{r \in R} Y_{sr} \cdot \varphi_r$$

### 2. Cost calculation

$$C_{D_d} = \hat{C}_D \cdot \mu_d$$

$$C_{L_d} = \hat{C}_L$$

$$C_{COL_{ds}} = \hat{C}_{COL} \cdot \sigma_{ds}$$

$$C_{STO_{ds}} = \hat{C}_{STO}$$

$$C_{TRA_{sr}} = \hat{C}_{TRA} \cdot \delta_{sr}$$

$$C_{TRE_r} = \hat{C}_{TRE_r}$$

$$C_{Out} = W_{Out}(\rho \cdot C_{L_d} + T)$$

## APPENDIX 2

Estimation for cullet price increase in the market

		$m_1$	$m_2$	$m_3$	$m_4$
Increase rate		20%	18%	10%	7%
Optimization scenario	1	55.00	45.00	21.45	17.00
	2	66.00	53.10	23.60	18.19
	3	79.20	62.66	25.95	19.46
	4	95.04	73.94	28.55	20.83
	5	114.05	87.24	31.40	22.28
	6	136.86	102.95	34.55	23.84



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