Journal of Environmental Management xxx (2012) 1–7

Contents lists available at SciVerse ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Environmental and economic assessment of a road safety product made with virgin and recycled HDPE: A comparative study

Carla L. Simões [a,*], Lígia M. Costa Pinto [b], C.A. Bernardo [a]

[a] IPC – Institute for Polymers and Composites/I3N, Minho University, Campus de Azurém, 4800-058 Guimarães, Portugal
[b] NIMA, Department of Economics, Minho University, Campus de Gualtar, 4710-057 Braga, Portugal

A R T I C L E I N F O

Article history:
Received 16 July 2012
Received in revised form
26 September 2012
Accepted 1 October 2012
Available online xxx

Keywords:
Life Cycle Assessment
Life Cycle Costing
Externalities
Plastics
Recycling
Anti-Glare Lamellae

A B S T R A C T

The development of value-added products made from post-consumer plastic recyclates has become an important goal in the quest for a sustainable society. To attain such goal, tools with higher accuracy and wider scope are increasingly necessary. The present work describes the application of a Life Cycle Assessment (LCA)/Life Cycle Costing (LCC) integrated model, with inclusion of externalities (environmental and social costs), to Anti-Glare Lamellae (AGL) made with High Density Polyethylene (HDPE). It compares an AGL currently manufactured from virgin HDPE (current AGL) with an alternative one made with recycled HDPE (optional AGL). The results obtained show that neither the current nor the optional AGL depict the best environmental performance in all impact categories. Nevertheless, there is a clear overall environmental and economic advantage in replacing virgin HDPE with recycled HDPE. The present work also makes evident that the LCA/LCC integrated model allows the identification of economic and environmental win–win and trade-off situations related to the full life cycle of products. As such, its results can be used as valuable guidelines in product development.

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1. Introduction

The production of waste has been increasing worldwide, making waste management an environmental, economic and social challenge (European Parliament, 2008). Current European Union (EU) legislation enforces minimum targets for packaging waste recovery and valorisation. Specifically, Directive 2004/12/EC requires that a minimum of 55%, by weight, of the total amount of packaging waste placed yearly in the market in all EU countries be recycled until the end of 2011. Additionally, a minimum recycling target of 22.5% for plastics packaging should be attained by that date (European Parliament, 2004). In Portugal, approximately 23.4% of the 378,068 tonnes of plastics packaging that went into the market in 2009 were selectively collected for recycling (InterFileiras, 2010). Therefore the target of the plastics packaging Directive was met in that year. There is also additional evidence that the overall packaging recycling target (59%) was met in 2010 (Sociedade Ponto Verde, 2012). The challenge now is to increase the recycling rates for other packaging materials, like glass. In any case, in Portugal, like in all EU countries, the ultimate aim of the legislation is to reduce waste deposition in landfills, promoting sustainability, and improving the technological and systemic capacity of recycling and valorisation. Several products that successfully incorporate recycled material from post-consumer plastic packages, such as profiles and textile fibres, already exist in the market (Korhonen and Dahlbo, 2007). One alternative goal is to increase the use of these recyclates in new sustainable viable higher-value products, such as road safety devices.

The sustainability assessment of products involves environmental, economic and social components (Gasparatos, 2010; Klöpffer, 2008; WCED, 1987). These components have to be properly considered and balanced if a new product is to be designed or an existing one is to be improved. Life Cycle Assessment (LCA) (Finnveden et al., 2009; ISO, 2006a) and Life Cycle Costing (LCC) (Ciroth et al., 2008) are sustainability tools that take into account the full life cycle (LC) of a product, from raw material extraction, production to use and final disposal. Only a systems approach allows recognizing, managing and avoiding conflicting trade-offs between the various situations and stages of its LC (Klöpffer, 2005, 2003; Norris, 2001). The LCA methodology that evaluates the environmental aspects and potential environmental impacts throughout a product's LC, is internationally standardized according to the ISO 14040 series (ISO, 2006a; ISO, 2006b). The LCC methodology is the economic counterpart of LCA. Up to the present, it has not been internationally standardized, although an international code of practice was recently published (Swarr et al., 2011).

* Corresponding author. Tel.: +351 253510320; fax: +351 253510339.
E-mail address: csimoes@dep.uminho.pt (C. L. Simões).

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http://dx.doi.org/10.1016/j.jenvman.2012.10.001

Please cite this article in press as: L. Simões, C., et al., Environmental and economic assessment of a road safety product made with virgin and recycled HDPE: A comparative study, Journal of Environmental Management (2012), http://dx.doi.org/10.1016/j.jenvman.2012.10.001

A LCC study is not a conventional cost accounting (Conventional LCC). The main difference between conventional cost accounting and LCC (Environmental LCC) is that the latter considers all costs associated to a product LC that are directly covered by one, or more, of the players involved in its LC (supplier, producer, user or customer, and/or final disposer) and includes the externalities that are anticipated to be internalized in the decision-relevant future (Ciroth et al., 2008; Swarr et al., 2011). LCA and LCC methods have already been integrated using different approaches (Bovea and Vidal, 2004; Hong et al., 2012; Huo and Saito, 2009; Kara et al., 2007; Keoleian et al., 2006; Kicherer et al., 2007; Lim et al., 2008; Rebitzer et al., 2003; Rüdenauer et al., 2005). Several authors stress the importance of accounting for the external costs (environmental costs) of the full LC (Ciroth et al., 2008; Swarr et al., 2011), although most studies normally do not consider them (Alonso et al., 2006; Castella et al., 2009). The LCA/LCC integrated model (Simões et al., 2012) adopted in this study consists in a parallel assessment, using the LCA methodology according to the ISO 14040 series (ISO, 2006a; ISO, 2006b), and the LCC methodology based on the Ciroth et al. (2008) guidelines. Fig. 1 represents the framework of this model. It consists in applying the LCA methodology to the product system and including its results into the LCC study, namely the Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) results. The goal and scope of the LCA should be consistent with the goal and scope of the LCC. The use of the same functional unit and system boundaries is a key issue (Rebitzer and Hunkeler, 2003). Finally, the results of the model are “portfolio presentations” of the LC cumulative total costs, combined with the environmental impacts identified during the LCA study as critical for the systems under analysis.

In this context, the present work describes the application of the LCA/LCC integrated model, with inclusion of externalities (environmental and social costs), to a specific product. An Anti-Glare Lamella, currently manufactured from virgin[1] High Density Polyethylene (HDPE) (current AGL), was chosen as a case study and compared with an alternative AGL made with recycled HDPE (optional AGL). In a previous work, the authors already did a comparative LCA study of these AGLs (Simões et al., 2010). Therefore this study will build on the earlier results. The overall goal of the LCA/LCC integrated model study is to identify economic and environmental win–win and trade-off situations related to the LC of the two AGL systems.

2. Life Cycle Assessment

Anti-Glare Lamellae are road safety devices used to protect highway drivers from the glare of the headlights of oncoming vehicles. As the functional feature of the AGL is equivalent for both systems, a single AGL was used as reference flow in this study. The system boundaries of both systems include all stages of the AGL LC, from the raw material production (virgin and recycled HDPE), to its manufacture by injection blow-moulding, distribution, use, and end-of-life (EoL). The recycled HDPE production includes sorting and compacting in the waste management facility, transportation to the recycler facility and production of the recycled raw material. Due to mandatory waste management regulations (European Parliament, 2004), the transportation to the waste management facility of the post-consumer packaging before sorting must always be done, independently of the final use of the packaging. Thus, in the previous study, this stage was not considered (Simões et al., 2010). The EoL scenario assumed that 57.7% of the AGLs are sent to landfill and 42.3% to recycling. The study was performed using the Eco-Indicator 99 (EI99) LCIA method (Goedkoop and Spriensma, 2001). The EI99 is a damage-oriented method (Simões et al., 2011) that considers eleven environmental impact categories. The impact categories are combined and quantified in three damage categories (*Resources*, *Ecosystem quality* and *Human health*). Finally, these damage categories may be aggregated into a single score, using weighting factors. Figs. 2 and 3 show, respectively, the LCIA characterization and normalization LC results of the two systems on a functional unit basis.

The LCIA characterization results show, in percentage basis, that the optional AGL system has a higher impact in practically all environmental impact categories (Fig. 2), with the exception of *Respiratory organics* and *Fossil fuels*. These results are consistent with previous published studies (Perugini et al., 2005, 2004) that showed environmental savings in non-renewable resources (crude oil, natural gas and coal), as well as reductions in air emissions, when using plastic recyclates from post-consumer containers instead of virgin plastics in the production of parts. The normalized results (Fig. 3) show that the highest environmental impact corresponds to the *Fossil fuels* category, followed by *Respiratory inorganics*. The first category is more relevant and larger in the current AGL system, and the other one in the optional AGL system. These results are due to the use of recycled HDPE in the latter, thus avoiding consuming oil to produce the raw material. On the other hand, more electric energy is used in the production of recyclates, thus enhancing gaseous emissions, which contributes to the *Respiratory inorganics* category. In order to identify the best alternative, due to trade-offs between these environmental impact categories, it is necessary to introduce a weighting step that will allow decision makers to rank of the two systems. Using the EI99 hierarchist (average weighting set) method, the single score results (expressed in Eco-Indicator points, Pt) are 0.812 Pt and 0.599 Pt, for the current and optional AGL, respectively. Therefore, in this scenario, the optional AGL has globally a more advantageous environmental performance. This is mainly due to the 82% reduction in the *Fossil fuels* environmental impact category that compensates the increase of the other impact categories.

Various objections have been raised to the use of a single score in LCA essentially due to the subjectivity of the choice of the corresponding weighting factors (Finnveden, 1997; Finnveden et al., 2009; ISO, 2006b; Pennington et al., 2004; Rebitzer et al., 2004; Rowley et al., 2012). Nevertheless, if used with caution, this indicator can convey a clear idea of the results of a LCA study to the different stakeholders. In the EI99 method, the problems associated with weighting have somehow been reduced by using a mixing triangle (only possible with damage categories) proposed by Hofstetter et al. (1999). The mixing triangle clearly shows the outcome of product comparisons for all possible weighting sets (each point within the triangle represents a combination of weights that add up to 100%). It also allows drawing the so-called lines of indifference. These lines that represent weighting factors for which the two products being compared have equal environmental loads, divide the triangle into areas of weighting sets for which one product is preferable to the other. Fig. 4 presents the mixing triangle results for the two AGL systems, showing the line of indifference and the subareas with their specific ranking orders. Each point on the line of indifference presents the same single score for the two AGL systems. All points to the right of this line correspond to weighting sets where the optional AGL is environmentally superior to the current AGL, and where the EI99 hierarchist weighting set (corresponding to 40%; 40%; 20%), represented by Δ in Fig. 4, is located. Around 84.4% of all the possible weighting sets show the optional AGL as environmentally preferable. The current AGL will be environmentally preferable when higher importance is

[1] A term used in the plastics industry to signify a polymer that has not yet been processed.

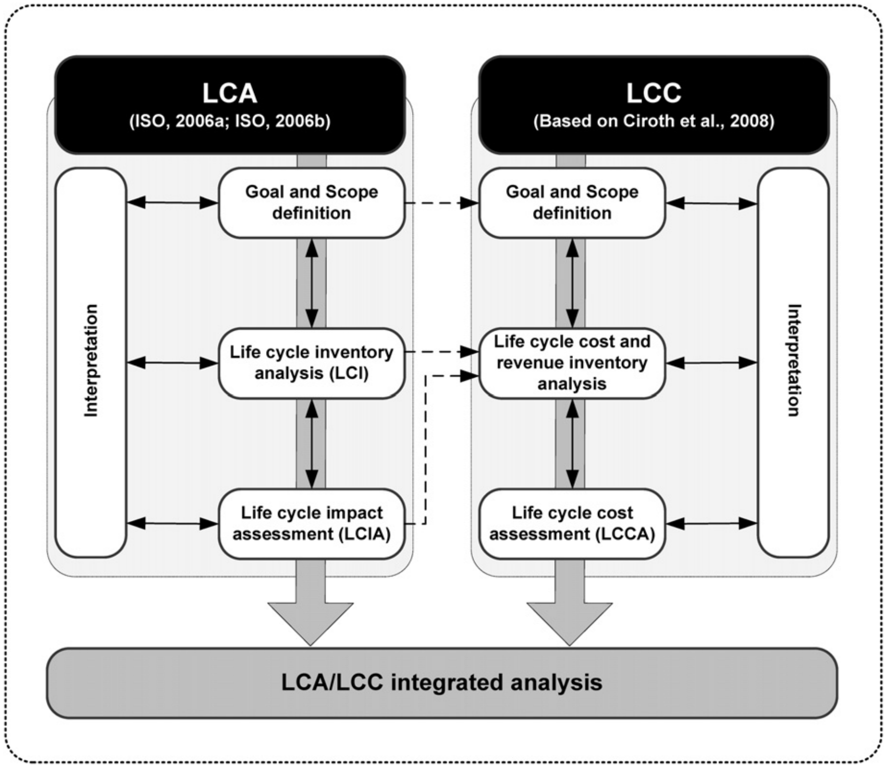

Fig. 1. LCA/LCC integrated model framework.

given to the *Human health* damage category (that is, its weighting is higher than to 83%). If the *Resources* damage category is rated lower than 2%, the current AGL will always be advantageous. On the other hand, if the *Resources* damage category is ranked higher than 17%, the optional AGL will always be advantageous. When the *Resources* damage category importance is between 2% and 17%, either the current AGL or the optional AGL could be environmentally preferable. Thus the mixing triangle enhances the transparency of the weighting process, and can help in decision making without actually imposing a specific set of weighting factors. Although, the weighting debate will always remain unsettled, this tool transforms the LCIA single score results into a consensus process instead of a procedure that generates single truths.

3. Life Cycle Costing

3.1. Goal and scope definition

A comparative LCC study of the current and optional AGL was performed in this work. The overall goal of the LCC study, built upon the previous LCA study results (Simões et al., 2010), was to identify and compare all cost drivers associated with the LC of the two AGL systems. Hence the functional unit, systems boundaries and other relevant assumptions were the same as in the preceding LCA study. The LCC of the two systems is based in a full LC perspective (producer perspective plus implications for market success, due to use and disposal costs). This perspective considers

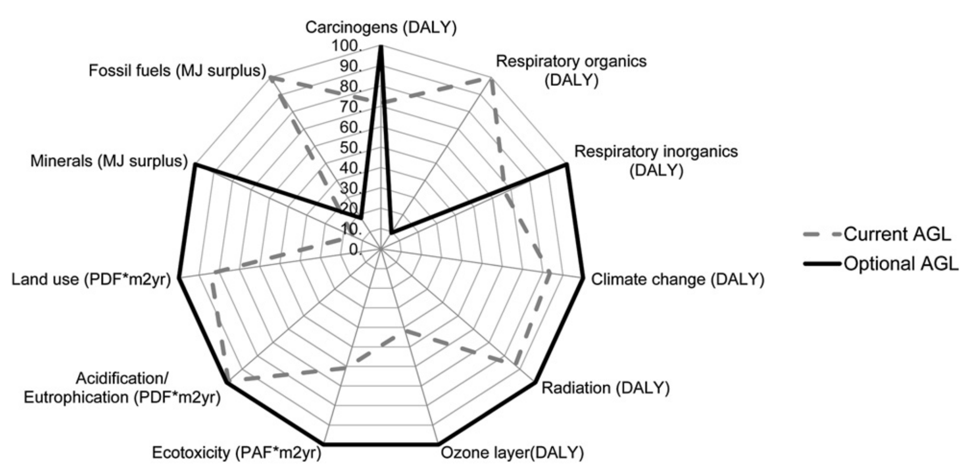

Fig. 2. LCIA characterization results of the two AGL systems, using the EI99 method (adapted from Simões et al., 2010). DALY: Disability Adjusted Life Years (years of disabled living or years of life lost due to the impacts); PAF: Potentially Affected Fraction (animals affected by the impacts); PDF: Potentially Disappeared Fraction (plant species that disappear as result of the impacts); MJ surplus: Surplus Energy (MJ) (extra energy that future generations must use to extract scarce resources).

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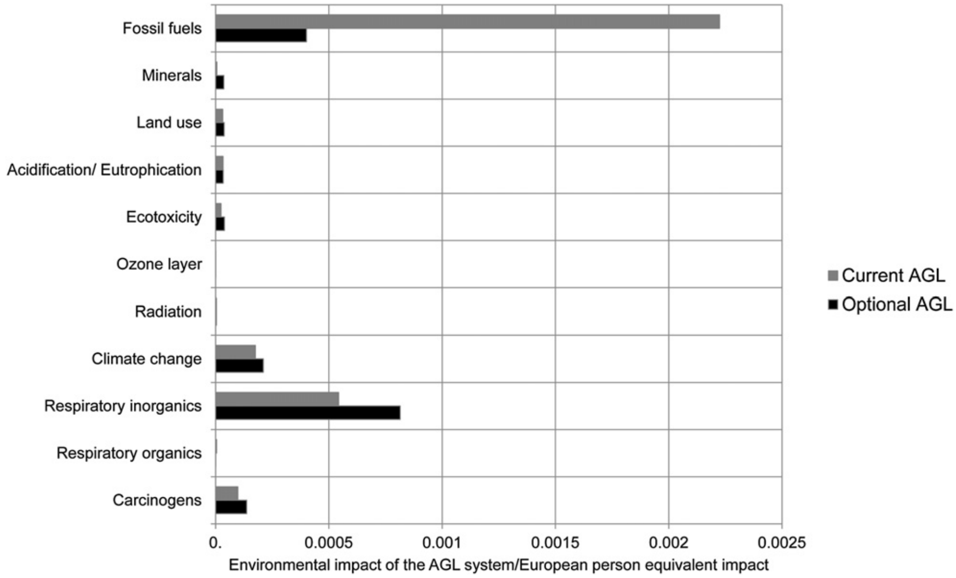

Fig. 3. LCIA normalization results of the two AGL systems, using the EI99 method (adapted from Simões et al., 2010).

the raw material (virgin and recycled HDPE) production, AGL production, distribution, use, and EoL treatment, and all intermediate transport processes (Table 1). The "producer" is the company that manufactures the AGL. The final "user" is the company that acquires the AGL from the manufacturer, installs them, and is responsible for their conservation. The "EoL" player is the waste management operator. The LCC reference year is 2010 and the discount rate used was 3.5% (Treasury, 2003).

3.2. Life Cycle Cost and Revenue Inventory analysis

Considering that a LCC accounts for all conventional costs plus the environmental and societal costs, all economic aspects to be considered in this study were identified and quantified. Table 1 illustrates the internal and external economic aspects included in this study. All direct (straightforward costs, such as materials, labour, utilities, etc) and indirect (less tangible costs, such as training, employee safety, etc) costs along the LC of the AGL were considered. Externalities that are anticipated to be internalized in the decision-relevant future, such as costs of CO_2 eq, SO_2, NO_x and fine particles emissions, were also considered. The quantification of CO_2 eq emissions was performed using the Intergovernmental Panel on Climate Change (IPCC) characterisation model. The Carbon price was obtained from the EU Emission Trading Scheme (EU ETS), which is a well-established market currently (Environment Agency, 2011). In a near future the CO_2 emission impacts may be extended to all companies, since they are one of the ways countries can use to meet their obligations under the Kyoto Protocol. SO_2, NO_x and fine particles emissions were identified as a cause of aggravated respiratory and cardiovascular diseases that can lead to premature mortality (Friedrich et al., 2001). These impacts are usually not included in the price of products; however, they should be considered when making decisions, since they imply a cost to society. The SO_2, NO_x and fine particles (<2.5 μm) emissions were directly quantified in the inventory. As in Europe there is no market transaction for these emissions, their prices were considered as damage costs (Watkiss and Holland, 2000).

The Life Cycle Cost and Revenue Inventory (LCCRI) done in this study include the LCI and LCIA results from the previous LCA study

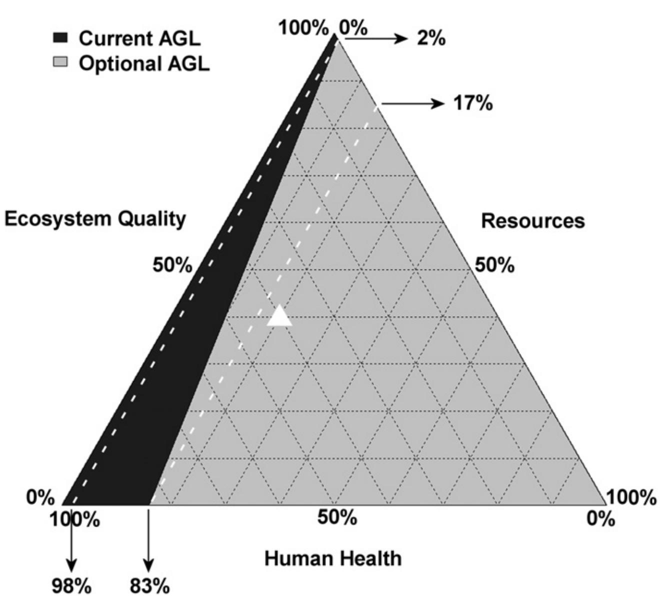

Fig. 4. Mixing triangle results of the two AGL systems, using the EI99 method.

Table 1
Economic aspects to be considered for the two systems.

Economic aspects	Input data	
Internal costs	**R&D (excluded):**	**Raw material Production:**
	- Market research	- Virgin HDPE
	- Development cost	- Recycled HDPE
	AGL Production:	- Material transport
	- Energy	**Distribution and use:**
	- Machines, plants	- AGL transport
	- Labour	**End-of-Life treatment:**
	- Waste management	- Landfill
	- Emissions controls	- Recycling
	- Transports	
	- Marketing activities	
External costs	Emissions – CO_2 eq	
	Emissions – SO_2	
	Emissions – NO_x	
	Emissions – particles < 2.5 μm	

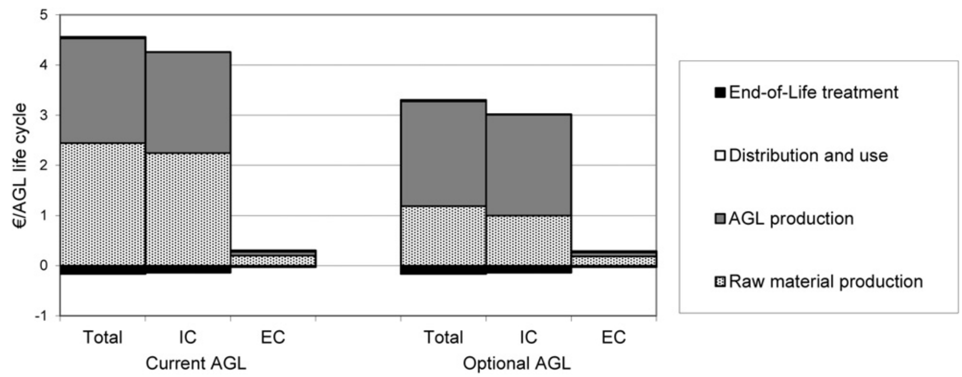

Fig. 5. Internal (IC), external (EC) and total costs of the two AGL systems.

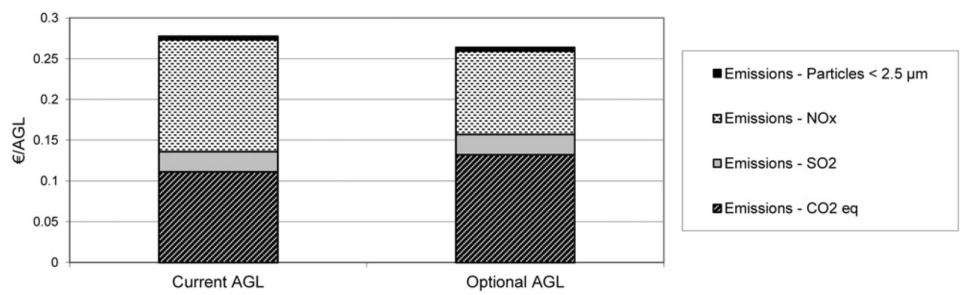

Fig. 6. External costs due to emission of the two AGL systems.

(Simões et al., 2010) and additional financial information. Market costs were used as conventional costs in all LC stages. The collected data was, when necessary, adjusted by price level, purchasing power parity and discount rates, to express all values in Euros 2010 (Portugal). All collected information constituted a database that allowed quantifying cost flows from every phase of the two AGL systems. During the LCCRI it was necessary to establish some assumptions. The Research & Development (R&D) LC phase was excluded, as it was considered to be the same for the two alternatives. The costs of the AGL production were not available; therefore they were estimated using general statistics from the Annual Survey of Manufactures of the U.S. Census Bureau referent to 2010 (U.S. Census Bureau, 2012).

3.3. *Life Cycle Cost Assessment and interpretation*

Fig. 5 presents the best estimation of the cumulative total costs of the two AGL systems on a functional unit basis. The two systems show a very different potential internal LC cost. This is due to the lower cost of the recycled HDPE compared to the virgin HDPE, as in fact the raw material cost is the only difference between them. The internal LC cost of the optional AGL is 30% inferior to the current AGL. Conversely, the systems depict a very similar potential external LC cost. In spite of the higher CO_2 emission cost of the optional AGL, that is compensated by the higher NO_x emission cost of the current AGL, as shown in Fig. 6. The EoL treatment has a negative cost, since it is a source of revenue due to the sale of recycled HDPE. In conclusion, the current AGL performs economically worse than the optional AGL, since it presents a higher total cost (internal plus external costs) throughout its LC. It can also be concluded that the optional AGL presents a total cost reduction of circa 29%.

It should be noted that the economic valuation of external costs (environmental and social) is a highly complex matter and there is still concern over the uncertainties related to its estimates (Ciroth et al., 2008). The main advantage of incorporating externalities in LCC and assessing all potential dimensions of a given product is the possibility of unifying the measurement unit, thus facilitating the decision making process (Simões et al., 2012). In order to clarify the LCC results, in the present work a sensitivity analysis was performed to the external economic aspects, using an alternative scenario purposely developed.

A key issue when including an externality in a LCC study is that it can be detected and an actual market exists for it (Simões et al., 2012; Swarr et al., 2011). Therefore, since there is no market in EU for SO_2, NO_x and fine particles emissions, these were excluded from the study in the alternative scenario. The Carbon price has also presented some volatility along the years. From 2005 to 2010, the EU ETS carbon price varied from under 10 €/ton CO_2 to over 30 €/ton CO_2 (Environment Agency, 2011). Like any commodity market, the carbon market faces uncertainty, being affected by several factors such as energy prices, weather conditions, institutional factors, policy ambiguity, etc (Chevallier, 2011; Creti et al., 2012). However the changing conditions imposed by compliance are unique to the EU ETS market. Because of the changing complexities of this market, forecasting prices is a particularly challenging and uncertain exercise (Koop and Tole, 2011). The Committee on Climate Change (CCC) forecasts a carbon price for 2020 of around 22 €/ton CO_2 whereas most market analysts forecast a price just below 30 €/ton CO_2 (in real 2008 prices) (Committee on Climate Change, 2009).

Table 2
Total cost of the two AGL systems for three 2020 carbon price scenarios.

2020 Carbon price scenarios (€/ton CO_2)		Current AGL (€/Life Cycle)	Optional AGL (€/Life Cycle)
Base	24.68	4.40	3.14
Lower limit	10	4.22	3.00
Upper limit	30	4.23	3.01

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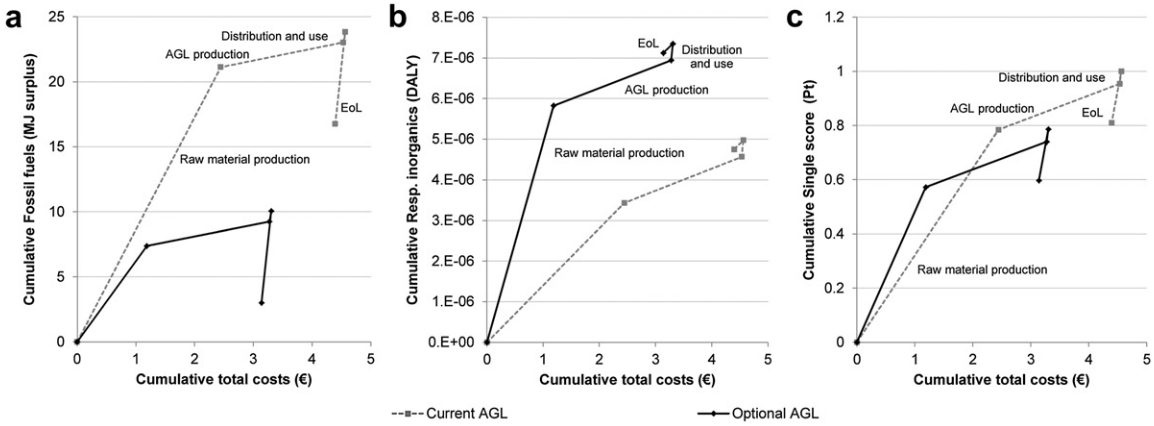

Fig. 7. Cumulative total costs versus (a) *Fossil fuels*, (b) *Respiratory inorganics*, and (c) single score indicator impact categories for the two AGL systems.

Two alternative scenarios, assuming a carbon price for 2020 between 10 €/ton CO_2 and 30 €/ton CO_2 (the price range in the operational years of the EU ETS market, whose higher limit is also the higher value forecasted by market analysts), are presented in Table 2, titled as "lower" and "upper limit", respectively. Both exclude SO_2, NO_x and fine particles emissions damage costs. In Table 2, a base scenario is also considered, assuming a carbon price for 2020 of 24.68 €/ton CO_2 (adjusted from the 2010 EU ETS average carbon price). It can be concluded that these scenarios would not change the global LCC conclusions, since the current AGL would still have the higher total LC cost, even though it has lower CO_2 emissions. This is due to the fact that the external cost is a small fraction of the total cost. In the base scenario, external costs constitute less than 9% of the total cost in both AGL systems, while in the alternative scenario they are less than 5%.

4. LCA/LCC integrated analysis

In order to perform an LCA/LCC integrated analysis, the *Fossil fuels* and *Respiratory inorganics* environmental impact categories were selected as the key environmental impact indicators. This selection was based in the LCIA normalization results that show the significance of each environmental impact in terms of scale of contribution. The *Fossil fuels* environmental impact category is of great relevance for the plastic industry, as oil is the main source of the raw materials and energy it uses in its production, strongly affecting their availability and price. The single score result was also selected as an environmental impact indicator, since it will depict the global environmental impact of the two AGL systems. The single score results are in this case quite robust, since the previous mixing triangle analysis showed that the EI99 hierarchist weighting set result coincides with the results of about 84.4% all of the possible weighting sets.

Fig. 7 shows the cumulative total costs (internal costs plus external costs) in combination with the key environmental impact indicators previously identified, for the full LC of the two AGL systems on a functional unit basis. In the figure, each different AGL LC stage, namely raw material production, AGL production, distribution and use, and EoL, are represented by a line segment. The results show that regarding the *Fossil fuels* and the economic impacts there is a win–win situation (Fig. 7a). In all stages of the optional AGL system, the *Fossil fuels* environmental impact and costs are always lower than those of the current AGL. However, with the *Respiratory inorganics* and the economic impacts, there is a trade-off situation (Fig. 7b). In fact, in all stages, the *Respiratory inorganics* impact of the optional AGL system is higher than in the current AGL, but the costs are always lower. Analysing the single score (global environmental impact) and the economic impacts, the results are similar to those of the *Fossil fuels* (Fig. 7c), that is a win–win situation.

The results show that even though the optional AGL is not always environmentally advantageous, this solution has an overall preferable environmental and economic profile. Thus, the use of recycled HDPE in product manufacturing should be considered, although its environmental performance during production must still be optimized. The recycled HDPE production has high gaseous emissions that contribute to the *Respiratory inorganics* category. The production of the electric energy necessary for recycling is responsible for this, and therefore should be acted upon. One possible strategy, to be implemented in the recycling facility, would be to increase the efficiency of the electric energy used. Another strategy, to be applied more globally, is the use of a higher fraction of renewable energy sources in the energy mix (Tsilingiridis et al., 2011).

5. Conclusions

The present work demonstrates how it is possible to minimize the overall environmental and economic impact of consumer products through the adequate selection of their constitutive materials in the design stage. In this case, the substitution of virgin for recycled polymer in the production of Anti-Glare Lamellae.

The LCIA characterization results demonstrate that the optional AGL system (recycled HDPE) has a higher impact in practically all environmental impact categories. The normalized results show, additionally, that the highest environmental impact of the current AGL (virgin HDPE) corresponds to the *Fossil fuels* category, while for the optional AGL the *Respiratory inorganics* is the more relevant impact category. This is due to the avoidance of the oil necessary to produce HDPE in the optional AGL. Conversely, in this case, more electric energy is used in the recycling process, thus enhancing gaseous emissions. The single score mixing triangle results demonstrated that for around 84.4% of the possible weighting sets the optional AGL is environmentally preferable. The total costs (internal plus external costs) of the full LC of the current AGL system are higher than those of the optional one. The two systems show very different potential internal LC costs due to the lower cost of the recycled HDPE compared to the virgin HDPE. Conversely, they depict very similar potential external LC costs. A sensitivity analysis showed that the uncertainty in the external costs doesn't change the global LCC conclusions, the current AGL still having the higher total LC cost. This result is due to external costs being only

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a small fraction of the total costs. The LCA/LCC integrated analysis demonstrated that even though the optional AGL is not always environmental advantageous (and therefore the same applying to the recycled HDPE material), it has globally a better environmental and economic profile.

The overall goal of a LCA/LCC integrated model study is to identify environmental and economic win–win and trade-off situations related to the full LC of a given product system. It is an uncontroversial fact that the incorporation of external costs brings uncertainties into the LCC results. However, these costs can still be used as guidelines in product development, namely in material selection, processing technology selection, EoL management and in strategic planning and marketing.

Acknowledgements

Carla L. Simões wishes to thank the Portuguese Foundation for Science and Technology (FCT) for a personal research grant (SFRH/BD/60852/2009). The authors acknowledge the financial support of FCT to the Institute for Polymers and Composites (IPC) through Strategic Project-LA 25-2011–2012 (PEst-C/CTM/LA0025/2011). The present work was partially financed by the EU LIFE-Environment Programme project Ecovia (LIFE 05 ENV/P/000366). The authors also acknowledge the support and information provided in various phases of the study by the following firms and institutions: PIEP – Innovation in Polymer Engineering; Brisa – Auto-estradas de Portugal S.A.; Tratolixo – Tratamento de Resíduos Sólidos EIM; Ambiente S.A.; Cirera & Silva Lda.; BCI – Brisa Conservação de Infraestruturas S.A.; Lipor II and Plastics Information Europe.

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