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Environmental sustainability for highways operation: Comparative analysis of plastic and steel screen anti-glare systems

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ABSTRACT

The road construction is one of the main responsible for resource use and has been targeted as criterion development in updated versions of the Green Procurement Policy (GPP) in Europe. Although major progress was achieved in road pavements and lightning systems during the past decade, discussions on the environmental sustainability of additional road elements can advance the current understanding on how to decrease the impacts on highways. The aim of this study was to compare the potential environmental impacts of two anti-glare safety devices used on highways: the plastic (polymer-based) and the steel screen (steel-based). To this end, we applied the life cycle assessment (LCA) methodology following ISO standards based on a cradle-to-grave approach. The impacts of both anti-glare devices are driven by the main raw materials. This condition means that the weight of products is a key issue when evaluating the sustainability of the anti-glare devices. The plastic anti-glare (PAG) consumes significantly less materials and thereby presents the most favourable environmental performance for all the impact categories. For the products' manufacturing analysis, the hot-dip galvanizing was the process with higher impacts for both devices, as the setup kit of the PAG is also made from galvanized steel. Adopting sustainable strategies, e.g. product's recycling at end-of-life, use of recycled materials and product's setup with Li-ion battery, may provide an average impact reduction of 19% and 6% for the PAG and the steel screen anti-glare (SAG), respectively. A break-even situation for all the environmental impact categories occurs when the steel screen weight is reduced from 8.0 kg to less than 1.80 kg. Major attention has been addressed to road pavements and lighting system when evaluating the life-cycle impacts of highways, but our results highlight that the impacts of road sector can be offset by focusing in additional elements, such as the anti-glare device.

1. Introduction

The majority of the impacts of transportation sector resonates from road traffic due to fossil fuel combustion and brake and wear abrasion, even though the indirect emissions from road infrastructure also contribute to the environment degradation. Not surprisingly, worldwide public policies have been focusing on the replacement of fossil fuel transportation vehicles for alternative fuels, such as the use of electric vehicles in Norway over the past years (Huang et al., 2015; Santero et al., 2011). Although road construction activities constitute one of three main drivers of resource use in the European Union along with new dwellings and energy production (Huang et al., 2015; Steger and Bleischwitz, 2011), limited attention has been given towards the indirect impacts that can potentially be exerted. The impacts of infrastructure construction projects and road construction can be associated to a large amount of greenhouse gas (GHG) emissions emitted during raw materials acquisition, construction, maintenance and refurbishment of highway infrastructure (Abdelhader, 2016; Cass and Mukherjee, 2011; Huang et al., 2015; Marzouk et al., 2017). These facts highlight the need to expand the understanding of impacts posed by road construction and operation.

Some engineering companies began to set the GHG emissions of their projects as a primary target in an attempt to reduce the

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impacts of the sector (Barandica et al., 2013). Carbon initiatives, such as the carbon footprint, carbon disclosure project, GHG protocols, add value to the companies' brand and disclosure the business commitment to their corporate social responsibility (CSR), meanwhile innovative companies also understand that resource efficiency and carbon neutrality are crucial for their business to succeed (Barandica et al., 2013; Newman et al., 2012). At government level, the green public procurement (GPP) implemented by the European Union is an important tool to achieve environmental policy goals relative to climate change, resource use and sustainable consumption and production (EC, 2016a). The GPP defines environmental criteria that are regularly reviewed and updated and recommends to prioritize products that present lower environmental impacts based on solid scientific evidence (Cruz et al., 2016; EC, 2016a). Specifically regarding road design, construction and maintenance, several criteria are based on life cycle assessment (LCA) principles (EC, 2016b; Garbarino et al., 2016).

LCA is a methodology that evaluates the potential environmental impacts of a product system throughout its life cycle based on detailed life cycle inventory (LCI) of the inputs and outputs of a product (ISO, 2006a). The life cycle perspective allows the construction sector not only to account for the indirect impacts but also to design new projects envisioning the less environmental aggressive material, better ways for road maintenance and refurbishment. In addition, the methodology is scientifically robust and the use of several mathematical models to address all the environmental aspects reduces the uncertainty in decision making between different scenario options (Baitz et al., 2013; Cherubini et al., 2015). These attributes turned LCA into an important tool used by the European Union to define and review criteria for GPP. For instance, the road marking paint criterion development (EC, 2017; Kaps and Dodd, 2018) was supported by LCA to address the associated environmental impacts.

The design options of a road infrastructure can determine its sustainability and efficiency over the whole life cycle (Cantisani et al., 2018). Thereby, the design alternatives must prioritize the decrease of the associated environmental burdens to meet those previously mentioned initiatives. However, the designing alternatives aimed at environmental impact reduction are typically directed to road pavements and lighting systems. In this context, Newman et al. (2012), in a comprehensive literature review identified projects initiatives that aims to increase resource efficiency and carbon neutrality, which include plant-based bitumen alternatives, new lighting and signal technology that reduces energy use and costs, roadbases that reuse previous pavement layers as a resource material rather than virgin quarries and road surfaces using scrap tyres and plastic wastes as durable wearing surfaces. Similarly, Pasetto et al. (2017) also evaluated the impacts of the reuse of by-products and recycled materials on a motorway pavement; while the drainages, road markings and other site-specific road infrastructure were not included on LCA. As several alternatives to reduce road construction impacts were mainly associated with road pavements and lighting systems, this underscores the need to seek for other elements that have relevant contribution to overall impacts of highways, such as traffic signals, overhead gantries, anti-glare devices, among others.

The anti-glare devices are generally used on highways to prevent drivers from being dazzled by the headlights of oncoming vehicles (Simões et al., 2011, 2013). In Brazil, there are mainly two types of anti-glares: the steel screen that is also used to prevent pedestrian crossing on highways, and the plastic anti-glare that is a one-block, hollow unit made of a polyethylene cylinder-like material with elliptical cross-section (Simões et al., 2011, 2013). Both devices are setup on metallic guard-rails or New Jersey concrete barriers with fixing kits, aiming to avoid the glare effect adding security to drivers and preventing accidents on roads.

Glare is the visual effect of any bright light source that causes some form of disturbance to visual activities reducing the visibility of the driver or causing discomfort (Fullerton and Peli, 2009). The glare effect is mostly perceived by the drivers at night due to the oncoming cars' headlights, though during sunrise and sunset, the sunlight can also perturb the driver's vision. Therefore, due to the visibility reduction or temporary disability to see on-road objects, glare is an important parameter in highway engineering and has clear safety implications since visibility reduction may impair performance on visual tasks related to driving (Bagui and Ghosh, 2012; Fullerton and Peli, 2009; Hwang et al., 2018). The oncoming glare for cars at night can be controlled through anti-glare devices such as screen barriers installed on the median of four/six lanes divided carriageway (Bagui and Ghosh, 2012) or with plastic anti-glares. Tests on drivers' visibility have showed that a visual target is detected by larger distances when there is no glare from the oncoming car, thus glare is a factor that can significantly and directly degrade drivers' ability to see pedestrians at night (Borzendowski et al., 2015; Chenani et al., 2017). From an economic point of view, the decrease on time-travel requirement corresponds to positive (and indirect benefit) linked to the anti-glare barriers, as this device reduces the need of vehicle's deceleration, thereby decreases vehicle operation cost (Bagui and Ghosh, 2012).

Several LCA were published to evaluate the sustainability of road construction (Barandica et al., 2013; Burghardt et al., 2016; Cantisani et al., 2018; Cruz et al., 2016; Giustozzi et al., 2012; Huang et al., 2015; Mendoza et al., 2012; Miliutenko et al., 2013; Pasetto et al., 2017; Tähkämö et al., 2012). However, few studies were addressed to additional elements of road such as side works materials (Mendoza et al., 2012; Oliver-Solà et al., 2009) and anti-glare device (Simões et al., 2011, 2013). In addition, none of the reviewed papers compared anti-glare devices produced with different materials. In this context, this paper aimed to compare the impacts of the plastic anti-glare device (polymer-based) with the steel screen anti-glare (steel-based) through their life cycle.

2. Materials and methods

This study followed the ISO standards 14040 and 14044 (ISO, 2006a, 2006b) to evaluate the potential environmental impacts of the products, and the industrial system modelling was conducted with SimaPro® software. LCA is a methodology that avoids problem-shifting from one phase of the life cycle to another and between different impact indicators (Finnveden et al., 2009).

2.1. Goal and scope

The goal of this comparative LCA was to evaluate which anti-glare device leads to lower environmental impacts throughout their life cycle. The system boundaries were set as cradle-to-grave, i.e., encompassed all the anti-glare product system: from raw materials extraction and its processing, the anti-glare manufacturing, distribution, product setup on highways, the anti-glare maintenance/replacement and final disposal (Fig. 1). At the use phase, the concrete barrier production was not included on the system boundaries since the concrete barrier can be the same for both product systems.

The main characteristics of the compared product systems are presented in Table 1 and briefly described, as follows:

- Plastic anti-glare (PAG): Anti-glare device produced with extruded and blow moulded HDPE boards with setup kit made of galvanized steel;

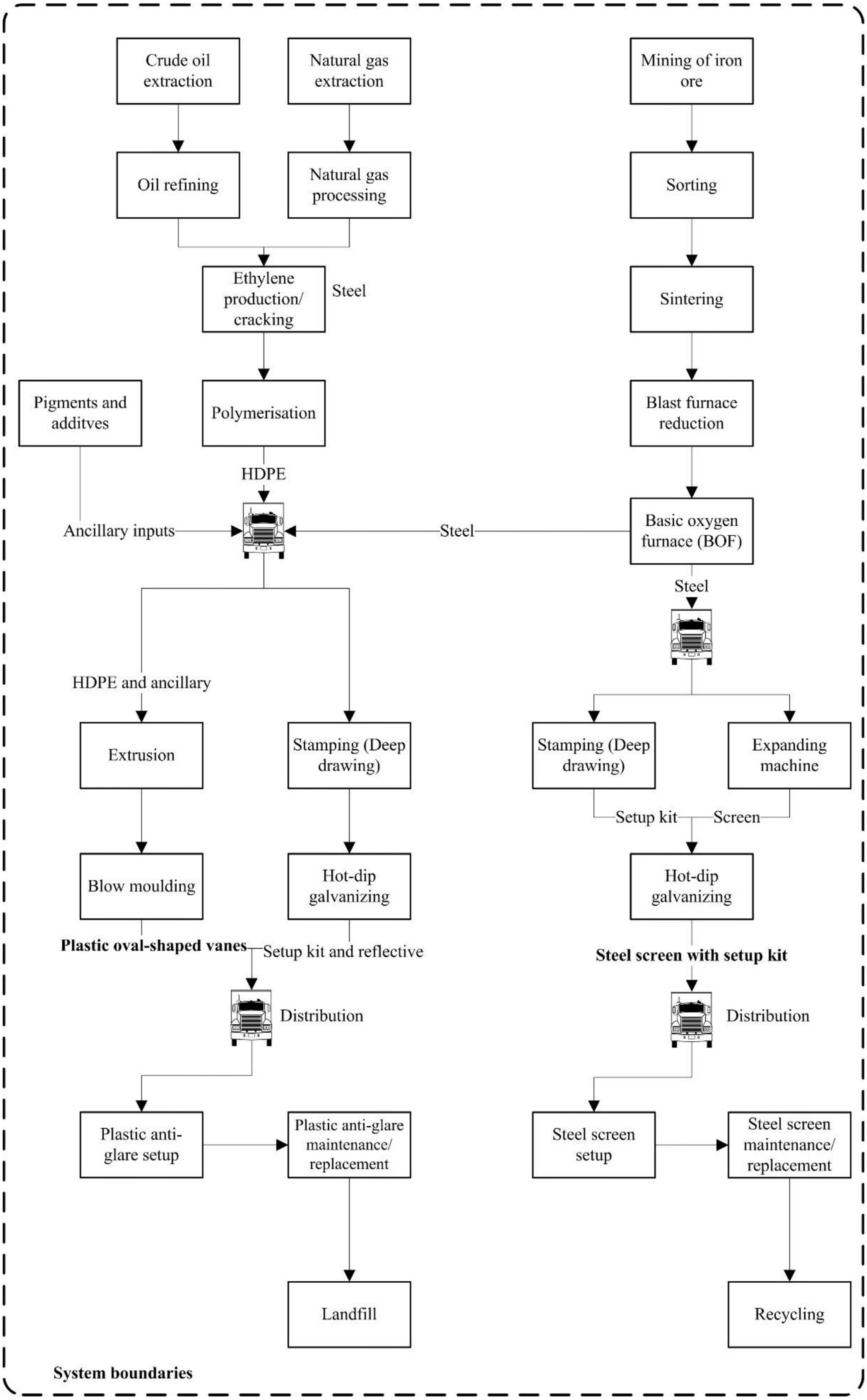
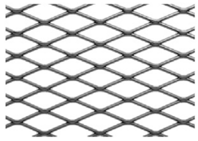


Fig. 1. System boundaries of the plastic anti-glare (PAG) and the steel screen anti-glare (SAG).

Table 1
Main characteristics of each product system under analysis.

Characteristics	PAG	SAG
Illustrative image		
Features	800 mm height	800 mm height
Predominant material	High density polyethylene (HDPE)	Carbon steel expanded sheet
Main material weight (kg.m^{-1})	1.35	8.00[a]
Setup kit	Galvanized steel (SAE 1020)	Galvanized steel (SAE 1020)
Setup kit weight (kg.m^{-1})	1.00	0.50
Lifetime (years)	10	10

[a] It was assumed a steel screen weight of 8.0 kg, although there are some other products weighing: 12.0, 16.0 and 20.0 kg.
Source: Industry data/estimative from DTS Dispositivos Ltda.

- Steel screen anti-glare (SAG): Anti-glare device produced with expanded and galvanized carbon steel sheet.

The function of anti-glare systems is to avoid disturbance of beam lights from oncoming traffic. It should further be highlighted, however, that the steel screen is a product that was not primarily developed to be used as an anti-glare system, although in Brazil it is also used to fulfil this function on the roads. Based on the anti-glare's function, the functional unit (FU) was defined as “To install and operate 1 linear meter of anti-glare system (height 800 mm) on concrete barrier (height 800 mm), given total height of 1600 mm from pavement) during 10 years”. Although the FU may not exactly express the product's performance relative to avoid disturbance of beam lights, the rationale for this FU was two-fold:

- We assume that both systems comply with the ABNT NBR 7941:2011 standard regarding the angle for the beam light avoidance, since this is a rather difficult function to be measured;
- We assume that both systems have the same technical performance to not jeopardize the steel screen product system, since this is not a product developed envisioning an efficient performance as an anti-glare device.

Since we assume the same technical performance for both systems, the reference flow can be used as equivalent to the functional unit (i.e. declared unit). The same definition was previously used by Simões et al. (2011, 2013).

2.2. Data collection

Foreground data for the PAG and SAG production were provided by DTS Dispositivos Ltda. PAG production used data directly measured by the manufacturer, while the SAG production used estimated data. The data of the setup and replacement steps of both PAG and SAG systems were also estimated. Background data were exclusively obtained from ecoinvent® database version 3.

2.2.1. Anti-glares production

Information on HDPE and steel production is described in Hischier (2007) and Classen et al. (2009), respectively. Extrusion and blow moulding data of the PAG boards and hot-dip galvanizing of the steel screen, as well as the setup kits of both product systems were obtained from ecoinvent® (Classen et al., 2009; Hischier, 2007), adapting the electricity grid of the datasets to represent energy produced in Brazil (Itten et al., 2012; Treyer and Bauer, 2016a, 2016b). To represent the process of expanding machine, a dataset for steel deep drawing (Steiner and Frischknecht, 2007) was used as proxy due to lack of data. The datasets used for anti-glare production modelling are described in Table 2. Production losses were based on expert estimative for both product systems, and accounted for 0.10% and 0.20% for the plastic and steel screen production, respectively. For the setup kits' production, the losses were 1.0% and 5.0% for the PAG and SAG systems, respectively.

2.2.2. Distribution, maintenance and end-of-life (EoL)

The products' distribution is by road, and since there are many possible destinations, it was assumed an average distance of 2000 km for both scenarios. The products' setup on highway uses energy from diesel generator of 5 kVA, while for PAG it is also used epoxy glue. While the SAG is continuously installed on the highway (i.e. without gaps between the screens) the PAG is installed with a 60 cm-gap at each product unit. In addition, for every 25 m of installed plastic anti-glare, the product has a reflective device coupled to the plastic board that is equivalent to 0.0006 m^2.linear meter^{-1} or 1.44 g.linear meter^{-1}. Although the PAG and SAG have a long lifetime, based on manufacture's recommendation we assumed a lifetime of 10 years with a yearly replacement rate of 2.0%. The product's maintenance is mainly due to losses from wind weathering exposure or car crashes and from human vandalism.

At the end-of-life (EoL), the baseline scenarios considered that PAG is further disposed to inert landfill while the SAG is recycled since it is very unlikely that steel would not be recycled. However, considering that the PAG also presents potential to be recycled, a sensitivity analysis was also conducted to account for the effects of recycling on this product system. The allocation of the environmental burdens of the open loop recycling between the product system (reference product) and the recycled material were based on the 50:50 allocation method. In this approach, the environmental burdens of the common life cycle stages (i.e. materials production and product's recycling) undergone by the product systems are equally divided. Table 3 shows a partially aggregated life cycle inventory (LCI) of the foreground data (i.e., gate-to-grave) used in the system modelling of the PAG and SAG devices.

2.3. Life cycle impact assessment (LCIA)

A hybrid LCIA method based on ReCiPe 2008 at the midpoint level (Goedkoop et al., 2009) and CML-IA (Guinée et al., 2002), IPCC (2013) and Cumulative Energy Demand (Jungbluth and Frischknecht, 2007), following the characterization models recommended by ILCD (EC-JRC, 2011; Hauschild et al., 2013) were used. The impact categories and the characterization models are listed in Table 4.

Table 2
List of datasets used for anti-glare life cycle modelling.

Life cycle stage	Input/output	dataset
Raw material	HDPE production:	Polyethylene, high density, granulate {GLO}| market for
	Steel production:	Steel, unalloyed {BR}| steel production, converter, unalloyed
Anti-glares' manufacturing	Extrusion process:	Extrusion, plastic film {BR}| production
	Blow moulding process:	Blow moulding {BR}| production
	Stamping press/expanding machine processes:	Deep drawing, steel, 3500 kN press, automode {BR}
	Galvanizing process:	Zinc coat, pieces {BR}| zinc coating, pieces
Anti-glares' setup	Energy for setup, products transportation and ancillary materials:	Epoxy resin, liquid {GLO}| market for[a] Machine operation, diesel, < 18.64 kW, generators {GLO} Transport, freight, lorry 16–32 metric ton, EURO3 {GLO}| market for
EoL	Landfilling:	Waste plastic, mixture {RoW}| treatment of waste plastic, mixture, sanitary landfill Scrap steel {CH}| treatment of, inert material landfill[b]
	Steel recycling:	Steel recycling[c]
Sensitivity analysis	Recycled HDPE:	PE post-consumer - 23′06′2017 (100% PCR) System[d]
	Energy for setup:	Battery, Li-ion, rechargeable, prismatic {GLO}| production
	Plastic recycling:	Plastic recycling[d]

[a] Only for Plastic anti-glare scenarios.

[b] Only for the scrap generated during products' manufacturing.

[c] Used the original dataset for steel production with the energy grid adapted to Brazil and with the exclusion of the intermediate product flow 'pig iron' since this input flow is replaced by the product being recycled.

[d] Dataset provided by a plastic company in the system format. For the plastic recycling the dataset comprises the HDPE flakes production, HDPE pellets extrusion and the wastewater treatment.

Table 3
Partially aggregated LCI of plastic anti-glare and the steel screen (gate-to-grave).

Inputs/Outputs[a]	PAG	SAG	Unit
Materials			
HDPE resin (GF3950)	1.531	-	kg
Colorlux/Colormix Verde Ral 6011	0.048	-	kg
Tinuvim 622 (BASF)	0.016	-	kg
Expanded steel sheet	-	9.459	kg
Carbon steel sheet SAE 1020 (setup kit)	1.192	0.620	kg
Carbon steel sheet SAE 1020 (reflective)	1.70E-03	-	kg
Epoxy Tecfix ONE quartzolit	0.034	-	kg
Processes			
Extrusion	1.568	-	kg
Blow moulding	1.535	-	kg
Expanding machine (anti-glare screen)	-	9.459	kg
Galvanizing (anti-glare screen)	-	0.568	m^2
Stamping (setup kit)	1.192	0.620	kg
Galvanizing (setup kit)	0.072	0.037	m^2
Stamping (reflective)	1.70E-03	-	kg
Galvanizing (reflective)	1.02E-04	-	m^2
Diesel generator (5kVA)	0.590	0.590	kWh
Transport of HDPE by lorry (16–32 ton) - 500 km	0.766	-	t.km
Transport of Ral 6011 by lorry (16–32 ton) - 500 km	0.024	-	t.km
Transport of Tinuvim by lorry (16–32 ton) - 500 km	7.98E-03	-	t.km
Transport of Expanded steel sheet by lorry (16–32 ton) - 500 km	-	4.732	t.km
Transport of SAE 1020 by lorry (16–32 ton) - 500 km	0.596	0.310	t.km
Transport of the Anti-glare by lorry (16–32 ton) - 2000 km	5.546	20.060	t.km
Products			
Plastic anti-glare with setup kit	2.774		kg
Steel anti-glare screen with setup kit		10.030	kg
Waste treatment			
Plastic losses to landfill	1.59E-03		kg
Steel losses to landfill	0.012	0.048	kg
Anti-glare with setup kit to landfill	100.0	-	%
Anti-glare with setup kit to recycling	-	100.0	%

[a] Unallocated flows considering the amount of inputs/outputs to produce the products and the replacement for 10 years.

For the impact assessment, the long-term emissions (>100 years), were dismissed due to the high uncertainty related to the modelling of these aspects. The facility infrastructure was not considered since this input has low environmental relevance considering the total product production in the facility during its lifetime.

2.4. Interpretation

The results were interpreted based on the LCI (Table 3) and the impact indicators characterized by the models presented in Table 4. In addition, to evaluate the sensibility of some assumptions made throughout the study and to guarantee robustness and reliability of the results and to assess strategies for impact reduction for both scenarios we conducted several sensitivity analyses presented in Table 5. This analysis comprises the 'baseline scenarios', that represent more realistic conditions established at scope definition, and the 'best case scenarios' that represent the best key-parameters (between those considered). Three levels of key parameters were

Table 4
Impact categories and characterization models.

Impact categories (category indicator)	Characterization model
Climate change potential (kg CO_2 eq.)	IPCC et al. (2013)
Ozone depletion potential (kg CFC-11 eq.)	WMO (2011)
Respiratory inorganics potential (kg PM2.5 eq.)	Rabl and Spadaro (2004)
Photochemical ozone formation potential (kg C_2H_4 eq.)	CML 2002
Acidification potential (kg SO_2 eq.)	CML-IA non-baseline
Water resource depletion (m^3)	ReCiPe 2008
Land use (m^2.a)	ReCiPe 2008
Resource consumption (kg Sb eq.)	CML 2002
Eutrophication potential (kg PO_4^{-3} eq.)	CML 2002
Cumulative energy demand (MJ)	Jungbluth and Frischknecht (2007) [a]

[a] Every flow in CED containing “feedstock” was excluded.

Table 5
Sensitivity analyses of assumptions and strategies for impact reduction.

Sensitivity analysis	Scenario	Description
-	*PAG [Baseline]:*	Plastic anti-glare produced entirely with HDPE from virgin sources. Product's setup using energy from diesel generators. Sent to landfill at EoL.
	SAG [Baseline]:	Steel screen produced with ~18% of steel scrap. Product's setup using energy from diesel generators. Sent to recycling at EoL (50:50 allocation approach).
EoL strategy and allocation approach	*PAG [EoL Rec. 50:50]:*	Plastic anti-glare sent to recycling at EoL and 50:50 allocation approach.
	PAG [EoL Rec. Cut-off]:	Vanes oval-shaped sent to recycling at EoL and cut-off allocation approach.
	PAG [EoL Rec. System expansion]:	Plastic anti-glare sent to recycling at EoL and system expansion approach assuming a 1:1 ratio of avoided HDPE and steel production from virgin sources.
	SAG [EoL Rec. Cut-off]:	Steel screen sent to recycling at EoL and cut-off allocation approach.
	SAG [EoL Rec. System expansion]:	Steel screen sent to recycling at EoL and system expansion approach assuming a 1:1 ratio of avoided steel production from virgin sources.
Use of recycled material	*PAG [Rec. HDPE]:*	Plastic anti-glare produced entirely with recycled HDPE.
	SAG [Increased Rec. content]:	Steel screen produced with up to 35% of steel scrap.
Energy source at setup	*PAG [Li-ion battery]:*	Plastic anti-glare setup using energy from Li-ion battery.
Best case scenarios comparison	*PAG [Best case]:*	Plastic anti-glare produced with recycled HDPE. Product's setup using energy from Li-ion battery. Sent for recycling at EoL (50:50 allocation approach).
	SAG [Best case]:	Steel screen produced with steel scrap content of 35%. Product's setup using energy from Li-ion battery. Sent for recycling at EoL (50:50 allocation approach).

evaluated in sensitivity analysis as presented in Table 5: i) Allocation approach, where different allocation methods were evaluated to deal with recycling process at EoL strategies; (ii) Recycled material as input, where recycled material was incorporated as an input in manufacturing of PAG (100%) and SAG (35%); and (iii) Energy source at setup, comparing Li-on battery alternative to the prior source (diesel-generator).

3. Life cycle impact assessment results

3.1. Environmental profile of baseline scenarios

The LCIA results effectively shows that the plastic anti-glare (PAG) has a better environmental performance than the steel screen anti-glare (SAG) for all the impact categories (Table 6). Besides the different material composition, i.e. polymer-based (PAG) and steel (SAG), the reduced consumption of raw material in the PAG production positively contributes to the environmental performance of this product. PAG has a significantly reduced weight compared to the SAG (reduction up to 72% considering the product and the setup kit - Table 3), which not only represents less material but also an added benefit for product's transportation that can be converted into an advantage for the environmental footprint of PAG. Overall, the PAG characterized results show an average impact reduction of 46% relative to the SAG.

For climate change, PAG can reduce the potential impacts by 58% (Fig. 3). The majority of the impacts from the PAG product system correspond to the polymer-blend (31.9%), mainly due to HDPE resin production and steel production for the setup kit (22.6%). These results corroborate by Simões et al. (2011), which reported the major contribution of the raw material production on the environmental impacts of plastic anti-glare life cycle. The authors

Table 6
LCIA results at midpoint level for PAG and SAG devices (per FU).

Impact categories	Unit	Plastic anti-glare (PAG)	Steel screen anti-glare (SAG)
Climate change potential (CC)	kg CO_2 eq.	8.84E+00	2.09E+01
Ozone depletion potential (ODP)	kg CFC-11 eq.	5.93E-06	1.11E-05
Respiratory inorganics potential (RI)	kg PM2.5 eq.	5.37E-03	1.61E-02
Photochemical ozone formation potential (POF)	kg C_2H_4 eq.	3.66E-03	1.06E-02
Acidification potential (AP)	kg SO_2 eq.	3.44E-02	1.03E-01
Water resource depletion (WD)	m^3 eq.	2.15E+00	7.48E+00
Land use (LU)	m^2a	7.41E-01	1.73E+00
Resource consumption (RC)	kg Sb eq.	8.09E-02	1.15E-01
Eutrophication potential (EP)	kg PO_4^{--} eq.	4.22E-03	1.51E-02
Cumulative energy demand (CED)	MJ	1.95E+02	2.17E+02

compared the current production of plastic anti-glare from virgin HDPE resin in Portugal with an alternative production route based on recycled HDPE. For the SAG, the production of the carbon steel expanded sheet is the main driver for greenhouse gas (GHG) emissions (41.7%). Even though steel production has lower environmental impact relative to the HDPE resin (1.9 kg CO_2 eq.kg steel^{-1}; 2.1 kg CO_2 eq.kg HDPE^{-1}) for climate change, these results are driven by the product's weight.

At the gate-to-gate analysis, impacts of the PAG's manufacturing processes is caused mainly by energy consumption, while for the SAG's manufacturing processes, the CO_2 eq. emissions are mainly associated with zinc production for the hot-dip galvanizing process. The energy use (considering both grid electricity and thermal sources in the facility) is somewhat higher for the PAG even though this product has minor material consumption/transforming. Fig. 2 shows the breakdown of energy consumption per processes of the PAG and the SAG manufacturing and setup per product unit (i.e. without the product's replacement at use phase). The product's manufacturing represents 88% of energy consumption for both product's systems while the product's setup on highways represents 12%. Analysing only the energy consumed at the factory gate (3.82 kWh.unit^{-1}), the blow moulding process contributes to 57.9% of energy use in the PAG's manufacturing, followed by the extrusion (30.6%) and the setup kit galvanizing (11.5%). The setup kit stamping consumes less than 0.1% of total energy usage in the manufacturing stage.

For SAG, on the other hand, the energy consumption of the hot-dip galvanizing process is responsible for almost all the energy used (99.7%) at the manufacturing stage (3.73 kWh.unit^{-1}), which demonstrates that this transformation process is the main driver of the climate change impacts at the factory. However, caution must be exercised against generalizations of these results, since the energy consumption and ancillary inputs of products' transformation were obtained from datasets of ecoinvent® database (i.e. secondary sources). In addition, for the steel sheet-expanding machine the stamping process dataset was used as proxy data due to the lack of more accurate data.

The steel-based product also presented the highest impacts on the maintenance stage because the impacts of the use phase are driven by the product replacement that follows the same environmental profile of the product, i.e. if the product has a worst environmental profile, this will result in worst environmental performance at the maintenance stage as well. Greater climate change impacts of the SAG compared to the PAG are also related to the weight of the products. Plastic anti-glare logistics (raw materials and distribution) follows the product's lower weight pattern, in terms of less transport usage in t.km, as demonstrated in Table 3.

For ozone depletion potential (Fig. 3), the impacts are caused mainly due to the blow moulding (39.1%) and extrusion processes (16.2%) in the PAG's production. The impacts of this process are related to the energy consumption from national grid, specifically linked to transmission lines losses, due to an effect called corona that emits N_2O to atmosphere (Dones et al., 2007; Itten et al., 2012). The steel used by the kit has also a significant contribution to PAG's manufacturing for this impact category (9.9%). For the SAG product system, the galvanizing process is the main responsible for the CFC-11 eq. emissions (34.4%), followed by the carbon steel production (23.4%) and the metalworking process (14.7%). N_2O also plays a key role on the ozone depletion impacts of SAG due to the transmissions losses and mainly due to explosives usage on mining operation from iron ore and zinc extraction.

For respiratory inorganics potential and photochemical ozone formation (Fig. 3), the impacts are caused mainly due to the raw materials production: 45.0% and 62.9%, respectively for PAG. For SAG, the carbon steel sheet production (31.9%) and the galvanizing process (36.5%) drive the impacts on respiratory inorganics. The respiratory inorganics are generated by Particulates $<2.5\ \mu m$ emissions from sparse sources along the supply chain, such as electricity consumption and steel on both scenarios and the epoxy production and HDPE production specifically for the PAG.

The potential impacts of photochemical ozone formation are from fossil carbon monoxide (CO) emissions on the iron sintering process for steel production. Therefore, the replacement of steel from the PAG's kit by other materials may reduce the photochemical ozone impacts on the polymer-based scenario. The C_2H_4 eq. emissions at manufacturing stage are due to energy consumption for polymer transforming and SO_2 emissions from zinc production for steel galvanizing.

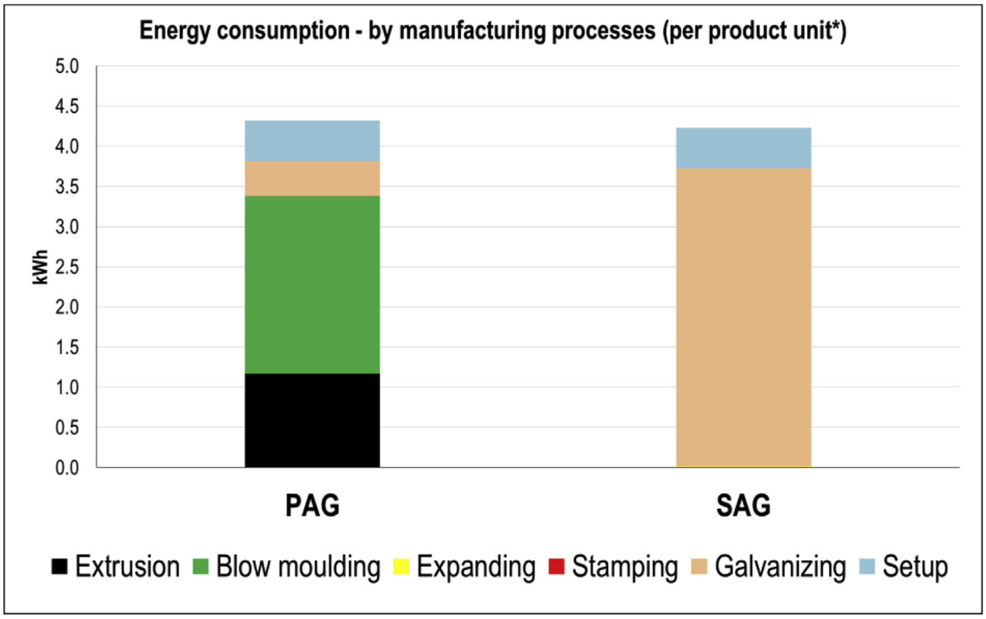


Fig. 2. Energy consumption (gate-to-use) per manufacturing processes. (* Unallocated energy consumption without product's energy for product maintenance).

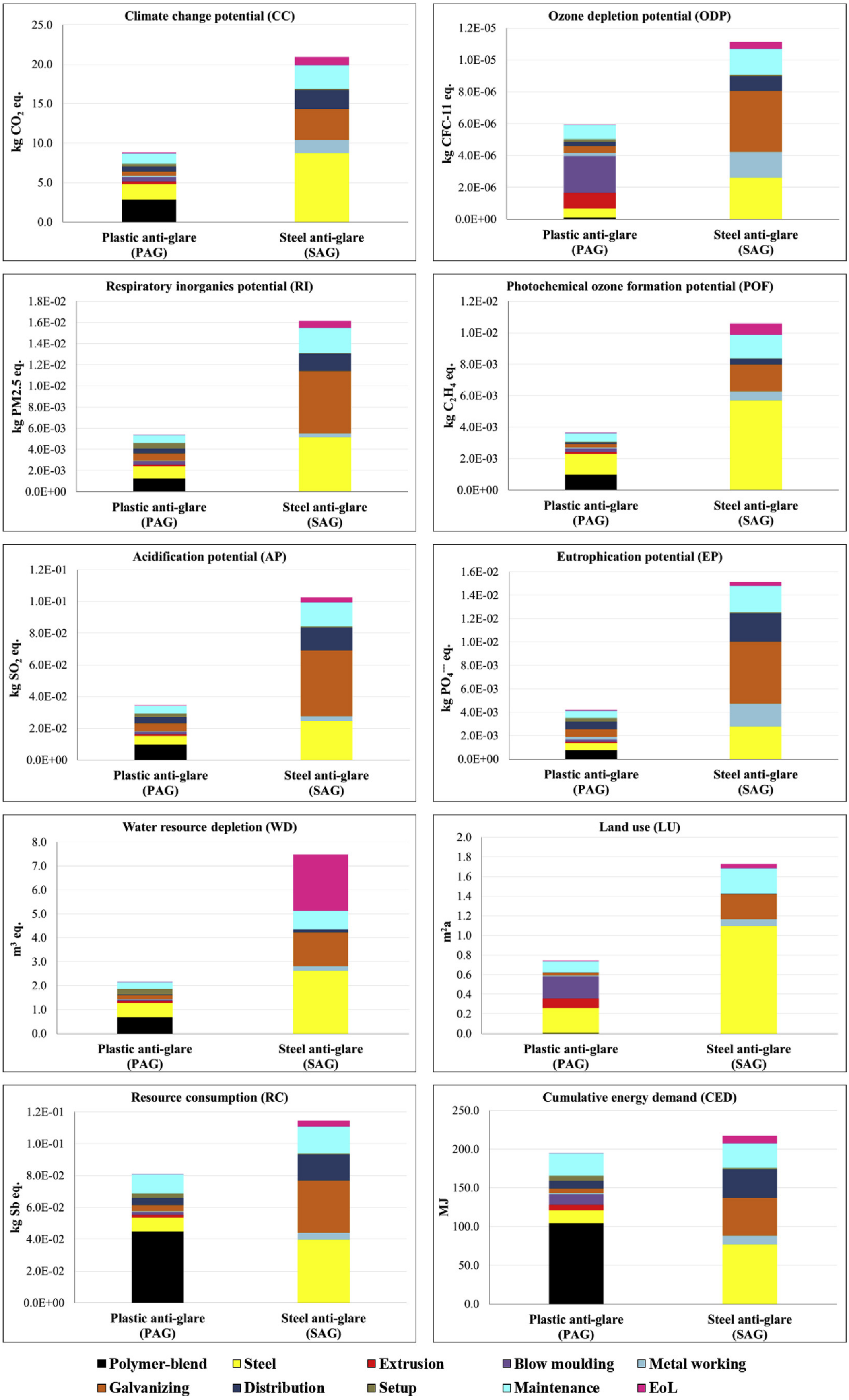


Fig. 3. Breakdown of the impacts per elementary processes.

The potential impacts of acidification and eutrophication (Fig. 3) showed similar patterns and drivers in both product systems. The raw materials production and the hot-dip galvanizing process are the main responsible for the impacts in both systems. For eutrophication, the burdens associated with wastewater treatment from the facilities also contributes with the PO_4^{-} eq. emissions. The polymer blend upstream chain is responsible for 28.4% of the acidifying emissions and by 18.2% of the eutrophying emissions on the PAG. Impacts from steel and the hot-dip galvanizing process are related to the SO_2 emissions aforementioned from the iron sintering process and zinc production. For these two impact categories, there is also a significant contribution of NO_x emissions from products' distribution.

Impacts on water resource depletion are due to polymer-blend production (31.3%) for the PAG and steel production for the PAG (28.8%) and SAG (35.1%). Water depletion on the steel upstream chain is related to the oxygen production that largely consumes water for cooling. The water footprint of oxygen production is also the hotspot for the impacts of the steel recycling process (Fig. 3). Therefore, even though the overall impacts of the SAG are reduced due to the product's recycling, there is a trade-off of the environmental burdens between the processes (i.e. decrease the impacts of raw materials but increase the impacts at the EoL). For the PAG product system, it can also be noticed that epoxy used during the setup stage also contributes significantly to water depletion.

The land use impacts are driven not only by the steel production (due to the charcoal usage on both scenarios), but also by the blow moulding (30.7%) and extrusion (12.9%) processes for the PAG. The impact of the plastics transforming on land use is due to use of electricity from the national grid. Although both product systems showed equivalent energy consumption at the gate-to-gate analysis (Fig. 2), for the steel-based product system a significant share of this energy comes directly from thermal sources, such as natural gas (energy source less intensive on land use) used in the facility.

For resource consumption and cumulative energy demand (Fig. 3), the materials production are the main drivers of the impacts considering the products' whole life cycle, as expected. The polymer blend represents 55.5% of the resource consumption impacts for PAG, while the steel sheet production contributes to 11.0% and 34.6% of resource usage in the polymer-based and steel-based scenarios, respectively. Other important sources of resource use correspond to the galvanizing process and products' distribution, due to zinc production and diesel consumed in the trucks, respectively.

For illustrative purposes, if we consider *BR*-040 that connects the states of *Goiás*, *Distrito Federal* and *Minas Gerais* (936.8 km of extension) in Brazil, 9,040 m of steel screen anti-glare devices were used over the construction period (Via 040, 2015). The associated practical implications in terms of climate change potential impacts, correspond to a potential emission of 189,269.4 kg CO_2 eq. from the SAG device, and would represent an emission of 79,870.6 kg of CO_2 eq. if PAG was installed on the *BR-040*. Considering the road construction life cycle based on ecoinvent® dataset (Spielmann et al., 2007), the PAG has an average contribution of 0.06% of total road impacts (ranges from 0.008% to 0.11%, depending on the environmental indicator); while SAG presents an average contribution of 0.14% of total road impacts (range of 0.02%–0.31%). This example clearly demonstrates that the road sustainability can be potentially enhanced through project design.

3.2. Sensitivity analysis

The results of the sensitivity of the EoL strategies and allocation approaches (Table 5 and Fig. 4a) show that for cumulative energy demand there is a trade-off situation, i.e. there is a swift in the most favourable scenario to decrease the environmental impacts. For this impact category, when considered the system expansion to deal with the open loop recycling at EoL, the SAG shows the best environmental performance when compared to the PAG sent to landfill [Baseline]. Nevertheless, if we consider that the PAG is recycled, regardless of the allocation approach, the PAG will always present the best environmental performance than SAG. Therefore, even if we consider that the SAG is recycled at its EoL and the PAG is sent to landfill, the results will be favourable to the steel-based system only for one impact category and if the system expansion is used as the allocation approach.

The use of increased steel scrap content (Table 5 and Fig. 4b) demonstrates that the SAG remains as the less favourable environmental scenario compared to the PAG produced with HDPE from virgin sources and the PAG produced with recycled HDPE. The use of recycled HDPE has the potential to reduce the PAG's impact in 06 environmental indicators. Higher impacts of the PAG [Rec. HDPE] for some categories may be unexpected at first glance, however it can be explained by the highest use of energy and the wastewater treatment in the recycling processes. Greater energy consumption from national grid increases the N_2O emissions due to transmission losses increasing the impacts on ODP. Likewise, the wastewater treatment increases the nutrient release on the environment.

Similar results were reported by Simões et al. (2011, 2013) comparing the plastic anti-glare production from virgin sources with the alternative recycled HDPE. The authors conclude that the use of recycled HDPE reduces the impacts on the non-renewable resource consumption and respiratory organics[1] impact categories but increase the impacts on the remaining indicators. Therefore, the use of recycled materials can reduce the impacts on several indicators but potentially increases the impacts on other indicators (i.e. trade-offs between the indicators).

The sensitivity analysis of the use of Li-ion battery, a cleaner technology, at products' setup (Table 5 and Fig. 4c) showed minor effects for the impact categories when considered the entire PAG's life cycle. The energy consumed at the product's setup has low contribution for the impacts when considered the whole life cycle. The environmental impacts of the PAG and SAG (please see section 3.1) are mostly driven by the raw materials and the hot-dip galvanizing process. For the polymer-based product, the replacement of the epoxy glue at the setup on highways can represent a more effective product improvement to decrease the impacts on water resource depletion rather the replacement of diesel generator by Li-ion battery. Evaluating only the impacts of the energy used at product's setup, the use of Li-ion battery represents an average reduction of 96% of the impacts. This result suggests that the Li-ion battery is likely an environmentally friendly option as compared to diesel generators.

The last sensitivity analysis was conducted to determine if the favourable results of the PAG product system were also observed in extreme scenarios (Table 5 and Fig. 4b). The results showed that even the best-case scenario for the SAG product system (considering the 50:50 allocation approach) has the worst environmental performance for all impact categories when compared to the PAG [Baseline] scenario. The PAG [Best case] can achieve an average impact reduction of 19% when compared to the PAG [Baseline] scenario. Comparatively, the SAG [Best case] represents an average reduction of 6% of the environmental impacts relative to the SAG [Baseline] scenario. Since the SAG [Baseline] consider the product's recycling at EoL, the environmental benefits of the best-case scenario of the SAG is somewhat reduced.

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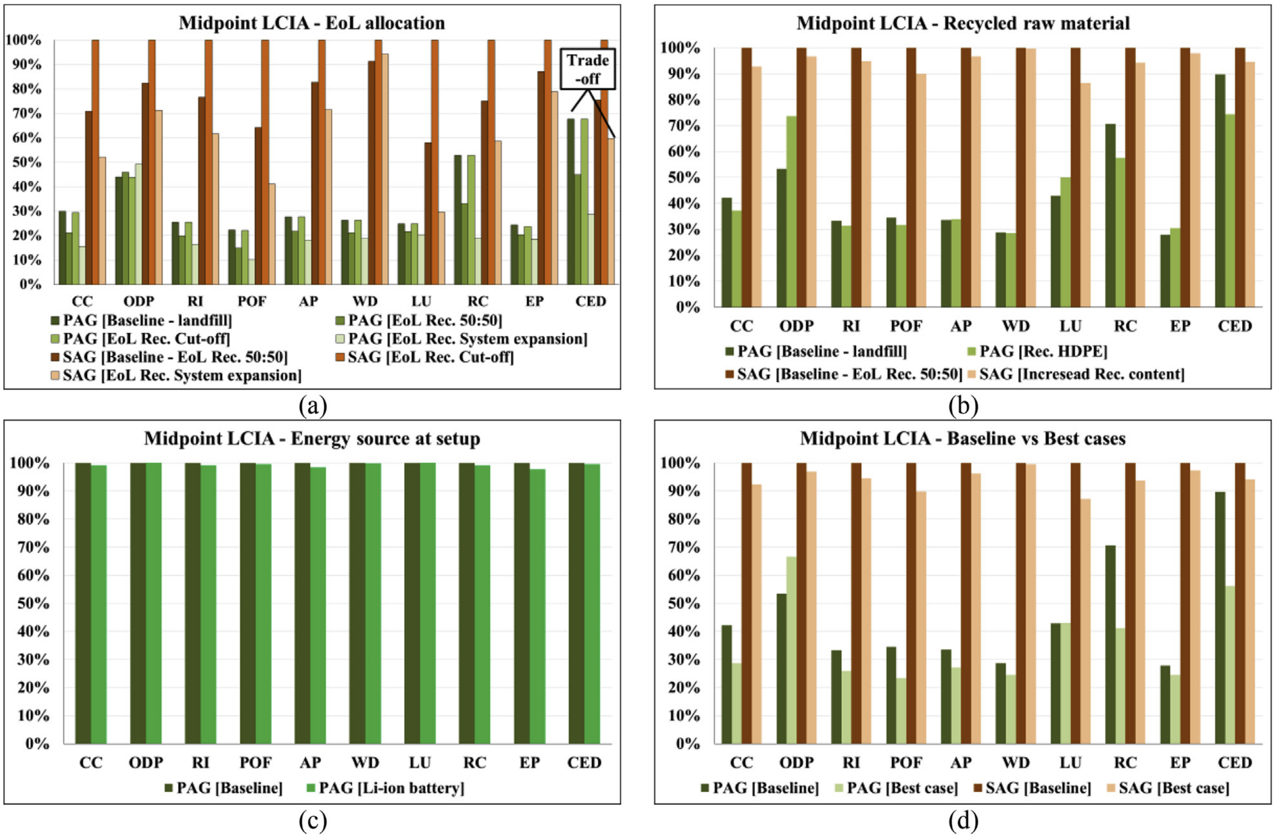
[1] Not assessed on this study since we use a different LCIA method.


Midpoint LCIA - EoL allocation

Midpoint LCIA - Recycled raw material

(a) (b)

Midpoint LCIA - Energy source at setup

Midpoint LCIA - Baseline vs Best cases

(c) (d)

Fig. 4. Sensitivity analysis on: (a) EoL strategy and allocation approach; (b) Use of recycled material; (c) Energy source at setup; (d) Best case scenarios comparison.

The break-even situation starts when the steel screen weight (Table 1) is reduced from 8.0 kg to 7.1 kg, which would give a total product's weight of 7.6 kg (with the setup kit). On this situation, the steel-based product shows a better environmental performance for the cumulative energy demand. The results can be environmentally favourable to the SAG for all the impact categories if the steel screen weight could be reduced to 1.80 kg (i.e. 2.35 kg with the setup kit), the same total weight of the PAG with setup kit. Naturally, in those cases, product design must be supported by technical feasibility.

3.3. *Results discussions*

LCA studies of anti-glare are scarce and therefore, our results cannot be directly comparable with other LCAs, but some conclusions can be drawn based on our outcomes and the LCA studies that compared products steel-based with HDPE-based. Stephens et al. (1998) and Keoleian et al. (1998) stated that at the inventory level the pollutants emission of the HDPE automotive fuel tank has lower impacts than the steel fuel tank, although for some flows the steel-based product has an environmental favourable result (e.g. the waste generation). Manuilova (2003) comparing packaging materials of chemical products from AkzoNobel also presented the trade-off between pollutants; however, for HDPE and steel drums, due to the different useful life of the products, the steel-based product was the environmental favourable option.

At the life cycle impact assessment level, the comparative LCAs from literature regarding the material with lower impacts, results were not converging either. Dlamini et al. (2011) also evaluated the impacts of the steel and HDPE automotive fuel tanks at impact assessment level, and the outcomes indicated that both products have similar environmental impacts, with a slight advantage for the steel product when considered pollution control strategies. Rives et al. (2010), comparing HDPE and steel containers for municipal solid waste management, showed that the steel-based product has a clear environmental advantage in mostly all the impact category indicators, with the exception to eutrophication (EP), photochemical ozone formation (POF) and human toxicity (this category was not evaluated on our LCA). Rives et al. (2010) outcomes are to some extent similar to ours, as the EP and POF impact categories along with water resource depletion (not evaluated on Rives' study) were the last indicators to reach a breakeven situation on our anti-glare case study. Differently from (Dlamini et al., 2011; Rives et al., 2010), Sharma and Manepatil (2009) and Hajibabaei et al. (2018) evaluated the mainframe assembly of a kid's tri-cycle and pipe materials for water distribution network, respectively, and concluded that at the cradle-to-gate approach the HDPE-based products had the best environmental performance.

Despite the contrasting LCA results between the different authors, a deep analysis of these studies shows that the product's weight drive the impacts and gives the direction whether the HDPE product is the most preferable option or not. In the LCAs in which the HDPE-based showed better environmental performance, this product had considerably lower weight than the steel-based product. Our results showed the same pattern, as for the baseline scenarios despite the SAG recycling at its EoL, the difference on the product's weight were crucial for the better environmental performance of PAG. This condition was clearly demonstrated by our breakeven analysis.

4. Conclusions

A comparative LCA performed with a polymer-based product -

the plastic anti-glare (PAG), and a steel-based product - the steel screen anti-glare (SAG), shows that for all environmental impact categories, the PAG device has a clearly better environmental performance. This result remains true even when extreme scenarios were compared. The SAG impacts can have an average reduction of 6% when considering an increased content of steel scrap and the use of a cleaner source for the anti-glare setup. Even with these strategies to reduce the impacts of the SAG, the PAG produced only with virgin sources and without resources recovery at its EoL remains as the most favourable scenario from an environmental perspective. The reasons for the environmental advantage despite the different product designs are mostly associated with the reduced weight of PAG compared to SAG. The environmental impacts of the anti-glare are driven by materials consumption more than the production processes alone. Nevertheless, there are opportunities to decrease the impacts of the production process as well, for instance, to avoid or reduce the need for hot-dip galvanizing of steel components used by both product systems.

A break-even situation for all the environmental impact categories occurs when the Steel screen weight is reduced from 8.0 kg to less than 1.80 kg. The use of recycled material is an alternative to reduce the impacts of both products. However, for the polymer-based product there are trade-offs between the environmental performance of virgin and recycled sources. The use of Li-ion battery can be considered a cleaner energy source to product's setup when compared to the diesel generator but for PAG, better results can be achieved for the water resource depletion impact category by excluding the use of epoxy glue.

The use of proxy data to represent the expanding machine for steel screen production and secondary data to represent energy consumption of the extrusion and stamping processes can be considered as limitations of this comparative case study. Therefore, to enhance the accuracy and representativeness of the environmental evaluation of anti-glare devices we recommend further studies that describe the inputs and outputs on metal and plastic transforming.

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