Journal of Cleaner Production 139 (2016) 548–560

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Environmental and economic life cycle assessment of a lightweight solution for an automotive component: A comparison between talc-filled and hollow glass microspheres-reinforced polymer composites

M. Delogu [a], L. Zanchi [a,*], S. Maltese [b,c], A. Bonoli [b], M. Pierini [a]

[a] Department of Industrial Engineering, University of Florence, via Santa Marta 3, 50139 Florence, Italy
[b] Department of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, via Terracini28 Bologna, Italy
[c] Magneti Marelli S.p.A. - Powertrain Division, Via del Timavo 33, Bologna, Italy

ARTICLE INFO

Article history:
Received 12 February 2016
Received in revised form
3 August 2016
Accepted 17 August 2016
Available online 20 August 2016

Keywords:
LCA
LCC
Automotive
Vehicle component
Light weighting
Composite
Hollow glass micro-spheres

ABSTRACT

Overall, light weighting strategies are mainly analysed in the aim of reducing impact during the use phase of a vehicle. In this paper environmental and economic assessments are combined to evaluate the sustainability of adopting an innovative lightweight material for an automotive component. The analysis is carried out according to the Life Cycle Assessment and Life Cycle Costing methods. A standard solution, based on talc filler-reinforced composite, and an innovative one made with hollow glass micro-spheres as plastic reinforcement, are compared to be applied to a vehicle dashboard. The use of hollow glass micro-spheres has expanded during the last years in the automotive sector, however evaluations of their environmental and economic performances along its whole life cycle have not yet been discussed extensively. In this study particular attention is given to the following aspects: i) balance between the use phase benefit and material production phase; ii) End-of-Life scenarios; iii) analysis of additional indicators besides CO_2 emissions; iv) data accuracy concerning manufacturing phase. Results show that hollow glass microspheres-reinforced composite is likely better from an environmental point of view for those impact categories where the use phase is more involved. The increase of material processing impact does not compromise benefits in terms of GWP and PED due to weight reduction, nevertheless it affects resource depletion and ecotoxicity indicators negatively. Overall the End-of-Life phase is not affected significantly. Moreover, despite a higher material cost, the innovative solution was found economically convenient as demonstrated also by the breakeven point (within the life distance).

1. Introduction

The automotive OEMs (Original Equipment Manufacturers) are currently requested to target some technological challenges to produce vehicles with a lower environmental impact (Kelly et al., 2015; Schmidt et al., 2004; Subic and Koopmans, 2010). The main objectives include:

- reduce Greenhouse Gas (GHG) emissions;
- reduce other emissions and hence improve air quality;
- increase efficiency and hence reduce consumption of energy and natural resources;
- increase recyclability and recoverability of vehicle parts thus reducing landfilled waste (Subic and Koopmans, 2010).

All these issues need to be kept in mind during the design phase of a new product. Previous works on this topic demonstrate that, beside technical feasibility, some important elements need to be considered when the applicability of innovative materials and design alternatives are evaluated.

The first element to be considered is that the objectives suggested by the current European directives (i.e CO_2 reduction during use phase) (EC, 2009, 2000) should be integrated with a life cycle perspective to build a comprehensive strategy to develop more environment-friendly vehicles and to avoid burden shifting from one phase to another (Witik et al., 2011). According to recent studies, the use of lightweight materials could lead to fuel saving and use phase emissions abatement, nevertheless it is often

* Corresponding author.
E-mail address: laura.zanchi@unifi.it (L. Zanchi).

http://dx.doi.org/10.1016/j.jclepro.2016.08.079
0959-6526/

List of Acronyms

OEMs	Original Equipment Manufacturers
GHG	Greenhouse Gas
EoL	End-of-Life
LCA	Life Cycle Assessment
FU	Functional Unit
ELVs	End-of-Life-Vehicles
LCC	Life Cycle Costing
LCIA	Life Cycle Impact Assessment
PED	Primary Energy Demand
HGM	Hollow Glass Microspheres
PP	polypropylene
PA	polyamide
ASR	After Shredding Residues
GWP	Global Warming Potential
ADP	Abiotic Depletion Potential
MAETP	Marine aquatic Ecooxicity Potential
ODP	Ozone Depletion Potential
EP	Eutrophication Potential
AP	Stratospheric Acidification Potential
HTP	Human Toxicity Potential
POCP	Photochemical Ozone Creation Potential
TEP	Terrestrial EcotoxicityPotenital
FAEP	Fresh-water Aquatic Ecotoxicity Potential
eLCC	Environmental LCC

responsible for increase in the production phase impact, particularly materials processing, thus preventing the expected benefit during use (Kelly et al., 2015; Kim and Wallington, 2013a). This sensitive balance between use phase benefits and production phase weakness is influenced by many aspects: powertrain system (i.e. Internal Combustion Engine vs. Electric Vehicles), material substitution ratio, material pair and vehicle part (Kelly et al., 2015). As a consequence, careful data handling is necessary to obtain clear and reliable outcomes. In this view, data accuracy and calculation assumptions were found to be among the most important aspects when developing an LCA study in this field since the final outcomes are strongly dependent on data quality and methodology assumptions (Kim and Wallington, 2013b; Raugei et al., 2015a; Raugei et al., 2015b; Witik et al., 2011).

The second element to be considered is related to the indicators selected for evaluating the environmental performances. Beside the assessment of CO_2 emissions, other environmental indicators should be included (Hawkins et al., 2013; Raugei et al., 2015a; Raugei et al., 2015b), particularly for the production and the End-of-Life (EoL) phase analysis. The use of novel materials could imply environmental burdens for the former, which cannot be depicted by the single Global Warming Potential (GWP) indicator; thus the addition of indicators for resource depletion and toxicity could be important (Raugei et al., 2015a; Raugei et al., 2015b). Concerning the EoL phase, the outcomes from LCA should be necessarily integrated with considerations in terms of recyclability and recoverability (Tian and Chen, 2014).

The last element is the need for a wider sustainability approach when environmental evaluations are combined with economic and social ones to give a deeper insight for selecting the best trade-off among the three dimensions of sustainability (Pallaro et al., 2015; Schmidt and Taylor, 2008; Zanchi et al., 2016b).

Life Cycle Assessment (LCA) studies are already used by several companies in the transport sector for the Eco-Design perspective (Chatzinikolaou and Ventikos, 2015; Cichowicz et al., 2015; Del Pero et al., 2015; Spielmann and Scholz, 2004), and particularly in the automotive field, as demonstrated by the high amount of technical reports by car manufacturers (Mercedes-Benz, 2013; Renault, 2011; Volkswagen, 2012) and scientific publications (Bein et al., 2016; Dattilo et al., 2016; Finkbeiner and Hoffmann, 2006; Hawkins et al., 2013; Koffler, 2013).

The lightweighting strategies, in particular the substitution of traditional metals with lighter ones and composites is one of the most studied issues (Dhingra and Das, 2014; Kim and Wallington, 2013b; A. Mayyas et al., 2012; A.T. Mayyas et al., 2012; Raugei et al., 2015a; Raugei et al., 2015b; Tharumarajah and Koltun, 2007). On the contrary, few authors discuss and compare different composite solutions in detail (Das, 2011; Delogu and Pero, 2015; Luz et al., 2010) and only a limited number of authors combine environmental with economic life cycle-based evaluations (Schau et al., 2011; Witik et al., 2011; Zanchi et al., 2016a).

This paper presents a comparison between two different composite-based solutions for a dashboard panel manufactured by Magneti Marelli®. The first design uses talc filler-reinforced composite, while the second is based on the use of hollow glass microspheres with a lightweighting purpose.

The study has been developed trying to address the aforementioned aspects with the aim of developing a comprehensive sustainability assessment, where environmental and economic dimensions are combined. The environmental assessment is carried out according to the LCA methodology (ISO 14040, 2006), while the economic sustainability is evaluated by means of Life Cycle Costing (LCC) method (Hunkeler et al., 2008). Indeed the economic viability of lightweighting solutions must include and compare the production cost (materials and manufacturing) with the cost saving during the use phase. The environmental results are presented for a wider set of indicators with the main purpose of detecting the trade-off between use phase and production, as well as the difference between alternative End-of-Life scenarios.

The analysis is based on a detailed data collection including primary data directly measured during the industrial process. Regarding the material production, a particular focus is dedicated to the material employed in the innovative solution (Hollow Glass Micro-spheres - HGM). HGM are used in a variety of lightweight automotive applications (i.e. thermoplastics molding composite, structural foam and body fillers, interior parts) (Yalcin and Amos, 2015); in particular its use as thermoplastic filler (i.e. PP and PA) is suggested to produce lower-density injected molding filled plastics without compromising physical properties (3M, 2012). They are particularly used in filled polymer systems such as glass fibre and talc thermoplastics for their strength/weight optimum performance. They present several advantages: reduction and replacement of a certain amount of high density fillers resulting in weight reduction, without decreasing original mechanical properties; a faster cooling rate from the melt hence high productivity; dimensional stability; increased stiffness and heat distortion resistance; reduced thermal conductivity and dielectric constant (Yalcin and Amos, 2015). However, very little literature exists describing the eco-profile of HGM and its production process parameters (energy, chemicals) with the exception of patents reference (Kusaka et al., 2001; Tanaka et al., 2003). Thus present paper might also bridge the gap by providing literature review and also results discussion concerning this material.

2. Materials and method

This section includes: a description of all the relevant data and key parameters defined for the LCA elaboration, according to the four phases of the ISO 14044 (goal and scope, inventory, impact assessment and interpretation of results); the illustration of the perspective, assumptions and data used for the LCC evaluation.

2.1. Life cycle assessment

2.1.1. Goal and scope definition

The goal of this LCA study is to analyse and compare the environmental performances of two alternative design solutions – a traditional one and an innovative one – for a dashboard produced by Magneti Marelli® over its whole life cycle. From an Eco-design point of view the dashboard is an interesting part due to its mass and certain amount of plastic materials; this makes it particularly relevant even from an EoL perspective (Andriankaja et al., 2009; De Medina, 2006) since, according to the European directive 2000/53/EC on End-of-Life-Vehicles (ELVs), it is actually a component candidate to be removed for recycling.

In this study, the main improvement drivers are weight reduction and the consequent fuel consumption saving for the whole vehicle. Improvements in the manufacturing phase are even expected, as described in the following paragraphs.

The component at hand consists of three different polymeric material layers and the two solutions differ only in the bottom layer (Fig. 1) which is made of polypropylene reinforced with 25% talc (PP 65.40 U) and PP reinforced with 23% Hollow Glass Microspheres (PP 23 HGM) in the standard and innovative design respectively (Table 1).

The technical performances of the two alternative materials are reported in Table 2. One of the most important properties is the resilience since a proper shock load absorption due to dynamic stress (i.e. airbags opening) needs to be guaranteed. In this sense the talc is one the most commonly used filler and its mechanical performances are overall claimed and verified in the literature (Luz et al., 2010). When compared with talc, the PP 23 HGM presents a lower value of Izod Impact strength (23 °C) (used as a reference test); nevertheless it proved to be within the limit of acceptance (Table 2). This also represents a limit for manufacturing scraps reuse as the shredding treatment entails the loss of the mechanical performance of the material, already at the limit of acceptance.

Despite the aforementioned criticalities, the PP 23 HGM can be considered a valuable material to be used for the component at hand; its low density, 30% below the PP 65.40 U, is one of the main reasons allowing a component weight reduction around 16%. Moreover, improvements in terms of thermal and sound insulation, and aesthetic features are expected. The talc substitution with the HGM does not entail changes in manufacturing processes, thus avoiding investment cost for new equipment.

The Functional Unit (FU) of the present study is an automotive dashboard panel, supporting and housing all the instrumentation for the vehicle use, to be mounted on Alfa Romeo Mito 955 diesel engine, with a life-distance of 150,000 km for 10 years. It is considered the most important and complicated part of the automotive interior since it has to cover aesthetic, safety, rigidity and lightweight performances (Tian and Chen, 2014). The innovative solution is expected to provide better performance in terms of acoustic and thermal isolation, however the comparability is allowed by the same primary function.

The system boundaries (Fig. 2) include the following life cycle phases: materials production, component manufacturing, transport of materials and of the finalized dashboard to plant for its assembly to the vehicle, use phase and EoL treatments. Compounding and assembly processes have been neglected since they consist in low energy consumption and manual operations respectively.

2.1.2. Life cycle inventory

Data collection to quantify relevant inputs and outputs is described for each product life cycle stage. Manufacturing processes parameters (materials and energy flows) have been obtained by means of direct measurements on industrial processes, whereas data on raw materials production have been retrieved mostly from GaBi 6.3 (Thinkstep, 2016) and ecoinvent 3.1 (Ecoinvent, 2016) database.

2.1.2.1. Material production.

The material production phase encompasses raw material extraction and processing, whereas the matrix and fillers compounding process has been excluded from the analysis since its energy consumption can be considered negligible if compared with raw materials processing. Table 3 lists materials quantities and database processes for each dashboard solution, according to the design data (Table 1).

As for HGM, to the best knowledge of the authors, all the studies published so far regard their mechanical properties and technical feasibility (3M, 2012; Yalcin and Amos, 2015; Yang et al., 2011), whereas evaluations of the environmental profile of this material along its whole life cycle have not been published yet. As a consequence a review is presented in order to have more insights about raw materials and production process. The HGM applied to the component at hand have a particle size between 15 and 65 μm, an average particle density ranging between 0.12 and 0.6 g/cm3 and a glass composition, similar to traditional Pyrex® glassware, consisting essentially of the following components by mass %: SiO_2 70.0–80.0%, B_2O_3 2–6%, Na_2O 3–8%, CaO 8–15% (3M, 2011).

Several production processes exist to produce HGM, differing on process type (i.e. dry, wet), foaming agent (i.e. sulfur component, silica gel), micro-spheres physical properties (Arai et al., 1998; Kusaka et al., 2001; Tanaka et al., 2003). In this study it has been assumed the dry process which comprises a melting phase of raw materials (e.g. SiO_2, B_2O_3) and foaming agents (i.e. Na_2SO_4) at high temperature, at least 1000 °C, to form a glass containing a large amount of a sulfur component. The glass is then dry-pulverized, dispersed and stayed in flame to foam the glass powder by using the sulfur component as a foaming agent. Thereby HGM of


(a) (b) (c)

Fig. 1. Automotive dashboard panel: Finalized component (a); Bottom layer (b); Upper mantle (c).

Table 1
Technical data dashboard design solutions (material quantities are referred to the finalized dashboard mass).

	Standard solution - PP 65.40 U	Innovative solution - PP 23 HGM
Total weight [kg]	4.722	3.962 (−16%)
Weight of bottom insert [kg]	2.49	1.712
Materials of bottom insert	PP reinforced with 25% talc	PP reinforced with 23% Hollow glass spheres
Other materials	Thermoplastic polyolefin TPO (1.12 kg) Isocyanate and polyol (1.122 kg)	Thermoplastic polyolefin TPO (1.12 kg) Isocyanate and polyol (1.122 kg)

Table 2
Mechanical properties of materials.

	PP 65.40 U	PP 23 HGM
Density (g/cm^3)	1.15	0.802
Flexural Modulus(MPa) (23 °C)	2500	2100
Tensile Strength, Ultimate (MPa)	20	13.9
Flexural Strength(Mpa)	35	25.2
Izod impact strength (23 °C) kJ/m^2	7	4.2
Vicat softening point(°C)	62	68.2

assuming the same energy consumption of the Pyrex process as the most similar among the process available on the commercial database (Table 3). This means that the borosilicate process, retrieved from ecoinvent, has been modified by applying the specific raw materials involved in the HGM composition (Table 3).

2.1.2.2. Manufacturing and assembly.
The manufacturing phase encompasses the processes depicted in Fig. 3; first the lower insert is produced by means of injection

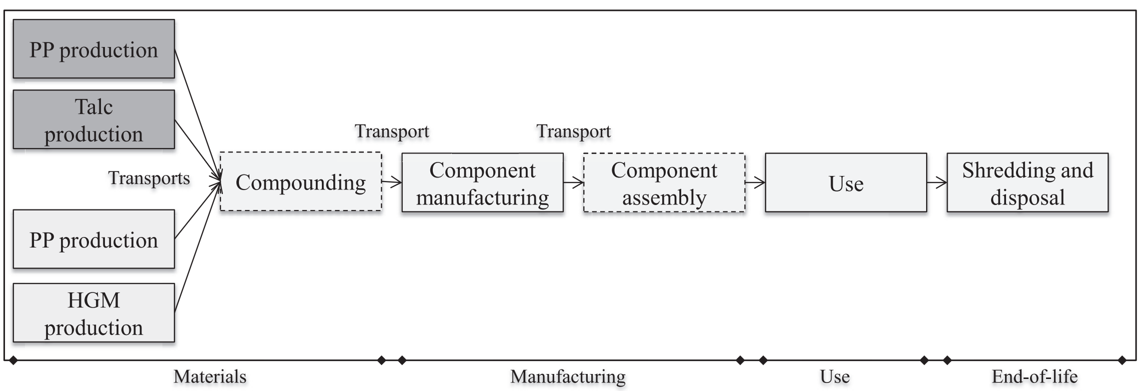

Fig. 2. Product system and system boundaries description. Compounding and assembly stages are excluded from the system boundaries (dotted line).

Table 3
Inventory data for material production phase (*gross value, including the scraps produced during the manufacturing phase).

Dashboard	Material	Quantity *	Unit	Process (GaBi; ecoinvent)
Standard solution - PP 65.40 U	PP	1.87	kg/FU	Polypropylene granulate (GaBi)
	Talc	0.62	kg/FU	Talcum powder (GaBi)
	TPO	1.94	kg/FU	Polypropylene/ Ethylene Propylene Diene Elastomer Granulate (PP/EPDM, TPE-O) Mix (GaBi)
	Isocyanate	0.28	kg/FU	Toluene diisocyanate (GaBi)
	Polyol	0.84	kg/FU	Polyether polyol (GaBi)
Innovative solution - PP 23 HGM	PP	1.46	kg/FU	Polypropylene granulate(GaBi)
	HGM	0.43	kg/FU	Silica sand; Boric acid production; Soda (Na2CO3); Lime (CaO) (GaBi); Glass tube production, borosilicate (Ecoinvent)
	TPO	1,94	kg/FU	Polypropylene/EthylenePropylene Diene Elastomer Granulate Mix (GaBi)
	Isocyanate	0,28	kg/FU	Toluene diisocyanate (GaBi)
	Polyol	0,84	kg/FU	Polyether polyol (GaBi)

borosilicate type glass are formed (Kusaka et al., 2001).

So the HGM production process has been modelled by including the raw materials, according to the specific composition, and

molding process then the upper part of the dashboard, the external visible layer, is manufactured via vacuum thermoforming process. The lower insert and the upper mantle are combined during the

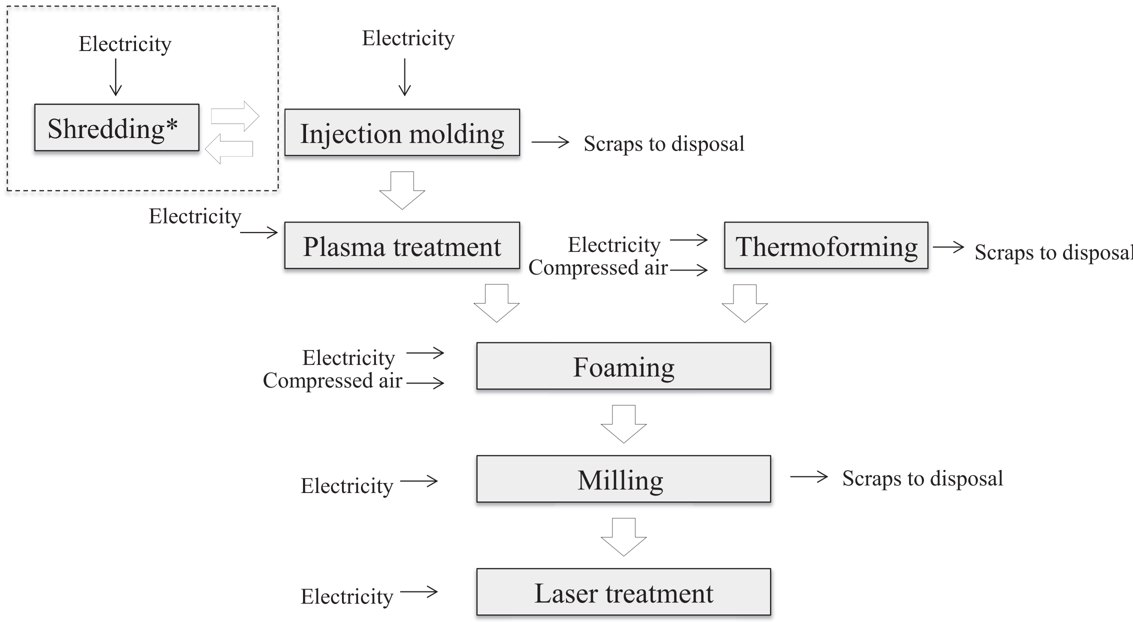

Fig. 3. Manufacturing processes flow (*shredding only in the case of standard solution).

foaming process and their final shape is regulated by means of milling process; a final laser processing is then developed.

The manufacturing phase of the two solutions differs only in the shredding of injection molding scraps (Fig. 3). The material used in the traditional solution allows a reuse of the injection molding scraps, after the shredding treatment; this is not possible for the innovative material whose mechanical properties decrease too much after shredding. The scraps flows stemmed from the other processes cannot be recycled and are disposed to landfill.

Data collection campaign was conducted on site during one 8 h shift; measurements were done every 15 min for each manufacturing machine and auxiliary facilities (air treatment, lightning, etc.). Energy and compressed air consumptions, and the scrap rate values are detailed in Table 4. The electricity country-mix specific of the countries involved in the processes are used; the compressed air production process was taken from GaBi. As for the innovative solution, these values have been calculated according to the cycle time, measured during the prototype production (Table 4). However, due to the large number of prototypes produced within one shift, these values can be considered representative also of a mass customization process.

The cycle time of the injection molding phase was measured for standard solution and during the testing phase of innovative solution; the latter was found 10% smaller (Table 4). The major fluidity of the innovative material - PP 23 HGM - compared to the standard one – PP 65.40 U – mostly influences the injection phase; in fact the lower thermal inertia of the glass microspheres compared to talc allows a faster cooling of the moulded component.

2.1.2.3. *Use phase.*

The inventory data for the use phase of the component is calculated by mathematical model that correlates the fuel consumption of the

Table 4
Electricity consumption, compressed air consumption, scraps rate and cycle time of manufacturing processes of the two solutions.

	Unit	Standard solution - PP 65.40 U	Innovative solution - PP 23 HGM
Injection molding			
Electricity	kWh/FU	3.2	3.05
Scraps	%	6% (reuse in the process)	9% (to disposal)
Shredding			
Electricity	kWh/FU	0.3	–
Plasma treatment			
Electricity	kWh/kg	0.19	0.29
Thermoforming			
Electricity	kWh/FU	1.41	1.41
Compressed air	Nm^3/FU	0.0798	0.0798
Scraps	%	42%	43%
Foaming			
Electricity	kWh/FU	1.32	1.32
Compressed air	Nm^3/FU	0.0798	0.0798
Milling			
Electricity	kWh/FU	0.19	0.01
Scraps	%	26.6%	26.6%
Laser processing			
Electricity	kWh/FU	0.18	0.21
Cycle time	sec	72	65

whole vehicle to the fuel use due to the component (Berzi et al., 2016a; Delogu et al., 2016b). For this study the analytical car consumption model, based on incremental approach, has been adopted (Koffler and Rohde-Brandenburger, 2009; Ridge, 1997). The consumption model is based on the following analytical expression:

$$fuel_{\ component} = c \times \frac{mass_{component}}{mass_{vehicle}} \times fuel_{vehicle}$$

where:

- c = fuel consumption reduction value (non-dimensional); a value of 0,6 is assumed (EUCAR, 1998; Riberio et al., 2007);
- $fuel_{vehicle} = \frac{fuel_{100\ km}}{100} \times use_{km}$;
- $fuel_{100km}$ = vehicle fuel consumption for 100 km (Table 5) in the New European Driving Cycle (NEDC) condition;
- use $_{km}$ = travelled kilometres during vehicle life distance (Table 5).

According to this formulation, the fuel consumption due to dashboard during the given life distance is 13.5 kg and 11.3 kg for the standard and innovative solution respectively (3.9 kg per kg of mass).

For a comparative purpose, the analysis included CO_2 and SO_2 use phase emissions, since they are the only ones proportionally depending on fuel consumption. The emission values attributed to the component are calculated according to the following equation:

$$emissions_{\ component} = emissions_{vehicle} \times \frac{fuel_{component}}{fuel_{vehicle}}$$

Table 5 shows technical data referring to car model equipped by the dashboard.

2.1.2.4. Transports.
The transport segments included in the analysis are representative of the real supply chain of the traditional and innovative solutions taking into account suppliers' sites, manufacturing plant site and assembly plant site (Table 6). Transports of raw materials have not been calculated as already included in the materials production dataset.

2.1.2.5. End-of-Life phase.
Many studies dealing with ELV issues in road transportation exist in the literature (Berzi et al., 2016b; Delogu et al., 2016a; Giannouli et al., 2007; Go et al., 2012; Schmidt et al., 2004). Overall, two important aspects need to be detected in the analysis of the EoL phase:

- Environmental burdens produced by the EoL processes;
- Recyclability and recoverability of the component.

Indeed, the ELVs directive explicitly states that “the requirements for the dismantling, reuse, and recycling of ELVs and their components should be integrated in the design and production of new vehicles” and sets minimum targets for the recycling (85%) and recovery rate (95%) by the year 2015. Following such procedure, the landfill disposal is discouraged and limited to 5% of the total vehicle weight (EC, 2000). The recyclability rate mainly depends on the possibility to dismantle components and recycle materials. This, in turn, depends on material types and availability of technologies for materials separation and processing. The recoverability rate instead takes into account also the benefit due to the energy recovery from waste incineration.

In this context, the ISO standard 22628:2002 (Road Vehicle – Recyclability and recoverability – Calculation method) provides the calculation method for designer to evaluate the recyclability and recoverability of a whole vehicle. According to the ISO, accessibility, fastening technology and proven dismantling technologies are the aspects mainly influencing the dismantling of components. The analysis of the potential dismantling of a component is approached by some authors in order to develop design-for-recycling specification sheets (Cappelli et al., 2007; Froelich et al., 2007; Justel Lozano et al., 2010); those studies demonstrate that enhancing the disassembly phase is one of the key aspect for achieving the recyclability target (Justel Lozano et al., 2010). This is particularly important when the lightweighting design goes in the direction of composites and multi-materials application (Justel Lozano et al., 2010; Go et al., 2012). Anyway, on-field investigations demonstrate that only few parts are commonly separated during the dismantling, while the rest is sent to shredding treatments (Berzi et al., 2013), thus a considerable contrast between guidelines/norms and real processes is suggested.

All the technologies involved in the EoL phase are responsible for impacts, mainly due to energy consumption and processes efficiency, which necessary need to be calculated and compared with the expected benefit from the material recycling and energy recovery; for this reason, beside recyclability and recoverability analysis, it is important to evaluate the EoL impacts according to the environmental indicators proposed in the LCA framework (GHK and Bio Intelligence Service, 2006; Ciacci et al., 2010).

Overall the dashboard is one of the components specifically mentioned to be separated according to the ELVs directive; as a matter of fact, its dismantling is currently impeded by three main aspects: i) it is difficult to remove; ii) its dismantling is a labor intensive activity; iii) it is unlikely recyclable, since different incompatible polymeric families are generally involved, thus limiting the use of current mechanical methods for the material separation (Ragosta et al., 2001; Tharumarajah and Koltun, 2010; Tian and Chen, 2014).

In this sense, the use of the lighter material – PP 23 HGM – does not seem to provide relevant variations for the EoL phase: the three layers are not physically separable in both cases (Fig. 4), and there are no current second uses for mixed granulate after mechanical treatments (Tian and Chen, 2014). As a consequence significant changes (advantages or disadvantages) could not be expected by the lightweight solution, with the exception of a lower landfilled waste amount due to a lower quantity of involved materials. However this aspect is supposed to play a negligible role.

For the above reasons the EoL phase of the dashboard includes

Table 5
Technical data referring to car model equipped by the dashboard.

Vehicle model	Alfa Romeo Mito 1.6, diesel (1600 cm3, 74 kW)
Vehicle mass [kg]	1355
Emission stage	EURO 5
Vehicle fuel consumption (mixed urban-extra) [l/100 km]	8.1
CO_2 emissions [g/km]	125
SO_2 emissions [kg/km]	1.05E-06
Use life-time [km]	150,000

Table 6
Transport segments (*GaBi dataset).

Segment	Means of transport	Distance (km)
PP from material supplier to material production site	Truck (30–40 t gross weight; 27 t payload capacity)*	983
HGM from material supplier to material production site		1290
PP 65.40U from material supplier to manufacturing plant		982
PP 23 HGM from material production plant to manufacturing plant		420
Dashboard from manufacturing plant to assembly plant		40

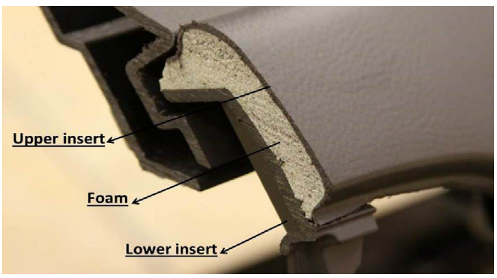

Fig. 4. Dashboard section.

the shredding treatment, assuming an electricity consumption of 95 kWh/ton (Tian and Chen, 2014), followed by two alternative treatments: After Shredding Residues (ASR) landfilling and incineration with energy recovery.

2.1.3. Life cycle impact assessment

The Life Cycle Impact Assessment (LCIA) is developed according to the eleven impact categories of the CML 2001 method (Guinée et al., 2002): Global Warming Potential (GWP), Abiotic Depletion Potential (ADP), Marine aquatic Ecotoxicity Potential (MAETP), Ozone Depletion Potential (ODP), Eutrophication Potential (EP), Stratospheric Acidification Potential (AP), Human Toxicity Potential (HTTP), Photochemical Ozone Creation Potential (POCP), Terrestrial Ecotoxicity Potenital(TEP) and Fresh-water Aquatic Ecotoxicity Potential (FAEP). The Primary Energy Demand (PED) is also included.Life Cycle Interpretation.

The results after characterization are first presented for each environmental indicator and the two EoL scenarios (landfill and incineration). Then a sensitivity analysis regarding the materials production phase is performed, in particular the sensitivity has been detected by changing the data used for HGM production process modelling.

2.2. Environmental life cycle costing

The Life Cycle Costing (LCC) has been suggested as a consistent framework for combining LCA and economic assessments (Schau et al., 2011). According to the SETAC guidelines (Hunkeler et al., 2008; Swarr et al., 2011) three types of LCC exist - conventional, environmental and societal. The Environmental LCC (eLCC) expands the Conventional LCC, usually focused on the individual companies cost, in order to be consistent with the system boundaries and assumptions of the LCA (Hunkeler et al., 2008).

The goal and scope of this eLCC study is to carry out an economic analysis of the two design solutions, described in more detail in Section 2.1.1, to give insights about economic trade-off between the production cost increase and the use phase expenditure reduction.

In the lightweighting design context the decision of implementing an innovative solution or not does make sense only if the production cost is compared with the benefits that this solution will produce in the use phase (in favour of the consumer). In this sense the user perspective is the most appropriate one; however in this study a 'hybrid perspective'[1] is applied since costs directly supported by the manufacturer (production and transport) are summed to the cost for the user without any added value.[2] In such a way the producer can evaluate the benefit for the consumer achieved by its higher expenditure and thus decide the proper price for the innovative solution.

The FU in this analysis is the same of the LCA (an automotive dashboard panel with a life-distance of 150,000 km for 10 years). The system boundaries include only those cost categories changing between the two solutions: materials for the bottom insert, manufacturing, transport and use. Materials of upper layer and foam, and EoL treatments are not included since are expected to be equal in both solutions; moreover EoL costs were generally found very small and not affecting the comparison between different material solutions (Witik et al., 2011). From the manufacturing point of view, the two scenarios differ for the cycle time value (Fig. 3), which influences the energy consumption, and the shredding process, which is present only in the case of standard solution (Fig. 3).

The manufacturing cost is modelled by considering the electricity and compressed air expenditures, whereas equipment cost and labour cost are not included since they are considered to be constant because the innovative solution does not require either new machines or additional employees.

The life cycle costs have been calculated using a steady-state model (Hunkeler et al., 2008); thus the use phase value is assumed as constant on time (a discount rate of 0). However, the breakeven point has been calculated also assuming a different discount rate in order to detect its influence.

The unit costs are given in Table 7; then they are combined with the electricity and compressed air consumption used for the environmental evaluation (Table 4). The use phase cost is calculated by multiplying the diesel unit cost and the fuel consumption from the use phase modelling (Section 2.1.2.3).

Moreover a cost sensitivity analysis has been done to investigate the parameters mostly influencing the total life cycle component cost: the material, energy and diesel costs have been varied according to a realistic fluctuation.

3. Results and discussion

3.1. Environmental assessment results

Environmental figures are shown according to the following life cycle phases: raw materials, including their extraction and processing; manufacturing, including energy and scrap flows due to production technologies; transports, including transportation of materials to manufacturing plant and dashboard to assembly plant; EoL, including shredding and disposal of waste.

[1] The 'hybrid perspective' concept is proposed in this study and represents a 'user perspective' where the production cost is assumed in place of the acquisition cost.
[2] Value added is defined as the "difference between the value of the outputs minus the value of the inputs purchased from others" (Heijungs et al., 2013).

Table 7
LCC inventory.

Life cycle phase	Flow	Unit cost	Source
Material	PP 65.40 U	1.45 €/kg	Primary data
	PP 23 HGM	3.3–3.9 €/kg	Primary data
Production	Electricity	0.12 €/kWh (average European price)	Eurostat, 2015
	Compressed air	0.04 €/Nm^3	Primary data
Transports	Transports	1.1 €/km	Primary data
Use	Diesel	1.26 €/litre (average European price)	Eurostat, 2015

Overall an impact decrease ranging between 2% and 16% was found for the innovative solution (PP 23 HGM) thus suggesting it as the likely design. On the other side, the different reinforcement material (HGM) is responsible for higher impacts in four categories (ADP elements, FAEP, MAETP and ODP) (Fig. 5 and "Supplementary material" section). This is mainly due to the raw materials involved in the HGM production phase, silica in particular, which produce a resource depletion (ADP elements) twofold larger than the talc processing. In the fiberglass industry this material is considered particularly sensitive but very strict specifications generally limit the use of alternatives (van Oers et al., 2002).

Different assumptions and goal and scope setting do not allow a numerical comparison between results from recent studies and the present one, nevertheless similar trends and considerations can be discussed. Indeed the contribution analysis shows that raw materials and use phase have the major impacts in overall dashboard life cycle (Fig. 5) thus confirming the outcomes from recent studies concerning the same component (Andriankaja et al., 2009; Tharumarajah and Koltun, 2010). Moreover, a trade-off between use phase and material production step is found, as generally stressed in the previous analysis about lightweighting (Raugei et al., 2015a; Raugei et al., 2015b). In this study, the use phase contribution reduction, associated with an increase of raw material impact, is found particularly in terms of resource depletion (−16% use phase, +90% raw materials) and ecotoxicity effects, while a slight trade-off is seen for the GWP (−16% use phase, +1% raw materials).

This demonstrates the importance of extending the environmental assessment to a diverse set of impact categories. It is evident that some impact indicators are mostly affected by the use phase (i.e. AP, GWP, POCP), whereas others are mainly influenced by the raw materials production (i.e. ADP elements, ODP). Therefore it can be suggested that to avoid burden shifting it is necessary to take into account all of them, though the interpretation of results could be more complex. Overall these results show that a comprehensive discussion of lightweighting benefits could be achieved only if the resource depletion and toxicity impacts are even included. Indeed, the use of the innovative material HGM allows to achieve the lightweighting purpose, in that a 16% mass decrease is reached thus leading to the use phase reduction around 16% along the whole environmental indicators. However this benefit is particularly evident in terms of GWP and PED, whose overall contraction is 8% and 5% respectively ("Supplementary material" section).

The accuracy of data collection, especially regarding the manufacturing phase, supports the idea that such phase (energy consumption) represents a low contribution if compared to the material and use phase ones (Das, 2011; Raugei et al., 2015a; Raugei et al., 2015b); nevertheless this should not discourage investigation on this phase in detail since non negligible effects can be observed especially when composite processes are involved (Witik et al., 2011). The manufacturing process influences energy consumption but also other significant aspects, as scrap rate and the final EoL recyclability (Raugei et al., 2014). In this specific case study, the innovative material enables around 3% energy saving, due to the low cycle time, and a 23% decrease in manufacturing phase contribution.

The EoL phase was found to be negligible when the landfill scenario is assumed, while the energy recovery from the final incineration makes this phase relevant in those categories sensitive to the energy process (Fig. 5). Overall, when the incineration scenario is assumed both solutions reach a lower impact in all the categories (due to the avoided burdens from energy recovery), therefore the landfill disposal is to be discouraged in any case with the exception of the GWP. However the different EoL scenarios – landfill or incineration - do not affect the comparison between the two solutions in a considerable way, and the innovative solution is likely to be considered better than the standard one.

The comparison between the two different EoL scenarios should be also done following the ISO 22682 statements, indeed the component design consequently influences the recyclability/recoverability of the vehicle. Previous studies did not provide insights in this matter; beside some papers addressing the component disassembly with recycling purpose (Froelich et al., 2007; Justel Lozano et al., 2010) no previous works discussed the evaluation of the component disassembly within the ISO standard and ELV directive frameworks.

Since the ISO standard only provides the guideline for the recyclability/recoverability of the whole vehicle, it can be argued that the manufacturer of component could only rely on internal and specific guidelines without a direct correlation to benefits in terms of ELV directive targets.

The present study tries to tackle this gap considering that only when the incineration scenario is assumed the mass of the dashboard could contribute to the recoverability index of the whole vehicle, whereas if the landfill scenario is applied its mass will not provide any benefit in terms of the ELV targets. This is generally in contrast with the ISO22628 statements in which the dashboard is specifically mentioned to be dismantled thus contributing to the recyclability rate of the vehicle. However a detailed analysis of the component shows that some technical features still impede its effective dismantling; therefore, from recyclability/reusability perspectives, two important design aspects need to be further developed in more detail: the assembly/joining techniques to join the mono-material parts and to fix the dashboard to the vehicle body-in-white; the materials selection according their compatibility in the same component. The use of few and simple assembling strategies could contribute to make the dismantling a less labor intensive activity thus enhancing the component reuse or its treatment in a dedicated line. The second aspect concerns the selection of compatible materials thus limiting materials heterogeneity and enabling materials treatment/separation by means of the current mechanical methods.

3.2. Economic assessment results

Economic assessment results are described according to the following cost categories: materials, manufacturing, transports and use. The perspective used in the analysis could mainly give information to the producer wanting to evaluate the development of the

Fig. 5. Environmental impact comparison between the standard (PP 65.40 U) and the innovative (PP 23 HGM) solutions (characterization results), for landfill (L) and incineration (I) scenarios.

innovative solution by comparing the benefit for the consumer and the higher expenditure necessary for its implementation.

The eLCC results in a total cost for the bottom insert (item) of 18€ and 16.6€ for the standard solution and the innovative solution respectively (Table 8). The cost breakdown, reported in Table 8, shows that material phase and use phase are the most relevant; in the standard solution their contributions correspond to 18% and 79% respectively, whereas they contribute 37% and 60% in the innovative one. An increase in the material cost is a general trend pointed out in other studies (Witik et al., 2011) and it is confirmed also in this specific case study. The trade-off between production phase and use phase expenditures is in favour of the lightweight solution, where the consistent cost saving during use phase (−30%) manage to counterbalance the material cost increase of the hollow glass spheres composite thus leading to a total cost reduction of 8%. A smaller but not negligible role is played by the lower cycle time

Table 8
Economic assessment results of standard and innovative solutions (*considering material average cost).

	PP 65.40 U	PP 23 HGM*
Material phase (€/item)	3.20	6.19
Manufacturing phases (€/item)	0.49	0.43
Injection Molding (€/item)	0.39	0.37
Shredding (€/item)	0.04	–
Plasma Treatment (€/item)	0.02	0.03
Milling (€/item)	0.02	0.001
Laser Treatment (€/item)	0.02	0.03
Transports (€/item)	0.14	0.11
Use phase (€/item)	14.3	9.94
TOTAL (€/item)	*18.17*	*16.67*

which leads to 13% manufacturing cost reduction, thus confirming the relevance of this parameter even from an economic life-cycle perspective (Witik et al., 2011). The transport cost does not significantly influence the total cost.

According to the assumed perspective, the innovative solution was found to be a feasible design for two main reasons: it produces significant cost reduction for the consumer while requiring a reasonable cost increase for the producer. This finding is also confirmed by the expected cost per mass saved, whose value was found between 3 and 4.3 €/kg $_{saved}$ and so in full accordance with the value generally accepted by the OEMs (3–10 €/kg $_{saved}$) (Heuss et al. 2012).

3.3. Combination of results

In order to evaluate the viability and the effective benefit expected by the innovative solution, the economic results were combined with the GWP, as one of the best known and applied indicator in the automotive sector. A systematic and recognized way to integrate LCA and LCC results is still missing and many authors approach different methods (Bierer et al., 2015). Moreover in previous studies concerning the automotive sector this is seldom discussed thus hindering comprehensive comparison and discussion of results (Schau et al., 2011; Witik et al., 2011). In the present study, an attempt was done by calculating the breakeven analysis and the CO_2 abatement cost[3] for the two design solutions.

The abatement costs stemmed from the PP 23 HGM solution was found between 0.5 and 0.8 €/kg CO_2 $_{saved}$; this appears still high if compared with reference from literature thus stressing the importance of material cost reduction to make the lightweighting a sustainable strategy from an economic point of view (Burgin et al., 2010).

The breakeven analysis is used to evaluate the convenience of a solution by identifying at which vehicle's life distance the lightweight solution could give environmental and economic benefit if compared to the standard one; GWP is normally used for the environmental part since it is particularly influenced by the use phase (Witik et al., 2011). As for the GWP, the innovative solution results in environmental convenience at 41,500 km (Fig. 6); this value is much lower than the total vehicle life span (150,000 km) thus suggesting the new material provides relevant environmental advantages, as also derived from LCA results. Concerning the economic convenience, the analysis was done both considering constant cost of the use phase and a discounting rate of 4% (Witik et al., 2011). When the diesel cost is assumed constant, the innovative solution crosses the standard one in the middle of the vehicle's life span (99,160 km) (Fig. 6); nevertheless when the discounting rate is applied the breakeven is delayed at around 148,000 km. Overall, these findings stress that the environmental benefit are achieved earlier in the vehicle's life span; thus the innovative solution can be considered preferable mostly from an environmental point of view.

3.4. Sensitivity analysis

The sensitivity analysis was carried out to examine the key data mainly influencing environmental and economic profiles. Due to the importance of HGM for the innovative solution, sensitivity analysis was done by changing the data used for its modelling. The environmental results are compared with outcomes from two alternative production process modelling: in the first – Fig. 7(b) – the HGM process is modelled by considering only the specific raw materials; in the second alternative – Fig. 7(c) – the borosilicate glass process is used without any modification. Results are presented only concerning four categories since similar considerations were drawn for all the other indicators.

It was found that the energy values are not significant: when they are excluded (alternative b) results are not significantly affected. The amount and types of raw materials seems to be more important, especially regarding ADP and MAETP, in fact a large fluctuation is seen between alternative a and alternative c.

The cost sensitivity analysis has involved the following parameters: material, energy and diesel. Each parameter was varied according to its expected fluctuation, in particular ±15% for the material cost (according to OEM estimates), ±37% for the energy cost (according to European countries scenarios) and ±50% according to literature (Witik et al., 2011).

Fig. 8 shows the cost sensitivity analysis for the two dashboard solutions. The material cost and electricity price stressed a negligible influence, whereas diesel cost presents the largest influence, ranging between 30% and 40%, which could affect the difference between the total costs of the two solutions also abolishing the economic convenience of the new one (Fig. 8). Indeed it can be argued that particular attention should be given also to the use phase modelling accuracy for the fuel consumption calculation.

4. Conclusions

This study evaluates the economic and environmental impacts in adopting an innovative lightweight material for an automotive component. In particular, the analysis deals with the comparison of a standard solution for a dashboard, based on talc filler-reinforced composite, and an innovative solution made with hollow glass micro-spheres as plastic reinforcement.

This study represents one of the first work including environmental and economic evaluations of the HGM application in the automotive sector. After a specific literature review regarding this material, it was found that the borosilicate glass process can be considered a good assumption for environmental evaluations. However, further efforts are needed in order to collect more specific data and model the HGM production phase in a more accurate way, especially regarding the raw materials.

Comparison of environmental performances reveals that this material is likely to be better than the talc filler-reinforced composite, in that it allows reaching significant weight reduction thus compelling with the most relevant challenges of the sector. In particular it gives benefits for those impact categories where the use phase is more involved (i.e. GWP, PED, AP), whereas indicators mostly affected by the material phase were found to become worse (resource depletion and ecotoxicity). Overall, the technical performances and the accurate data collection in the manufacturing

[3] The CO_2 abatement cost correlates the production costs and the avoided CO_2 emissions during the operating phase of a given technology (Wesselink and Deng, 2009).

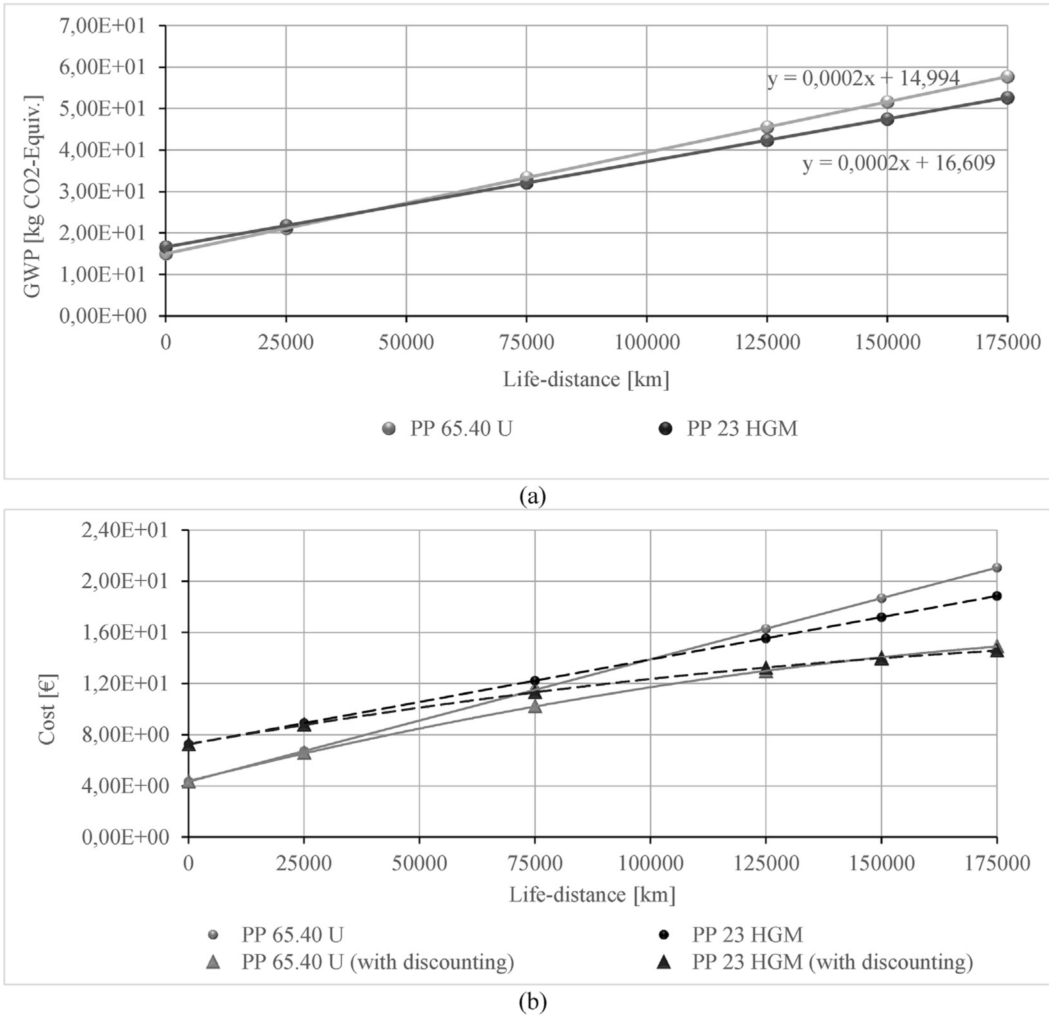

Fig. 6. Breakeven analysis for the environmental convenience (a) and the economic convenience (b).

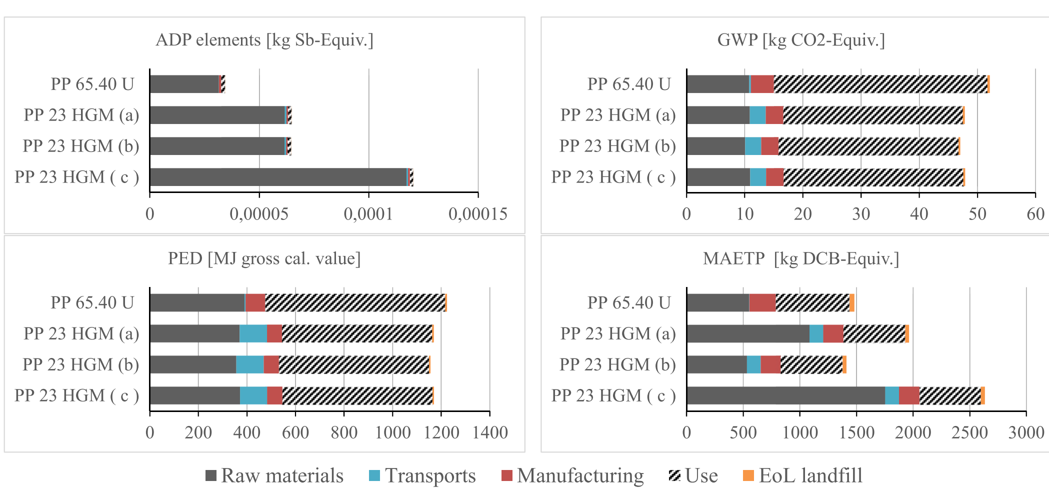

Fig. 7. Environmental sensitivity analysis about HGM production process (PP 23 HGM (a): specific raw materials and energy consumption from borosilicate glass process; PP 23 HGM (b): only specific raw materials; PP 23 HGM (c): borosilicate glass process).

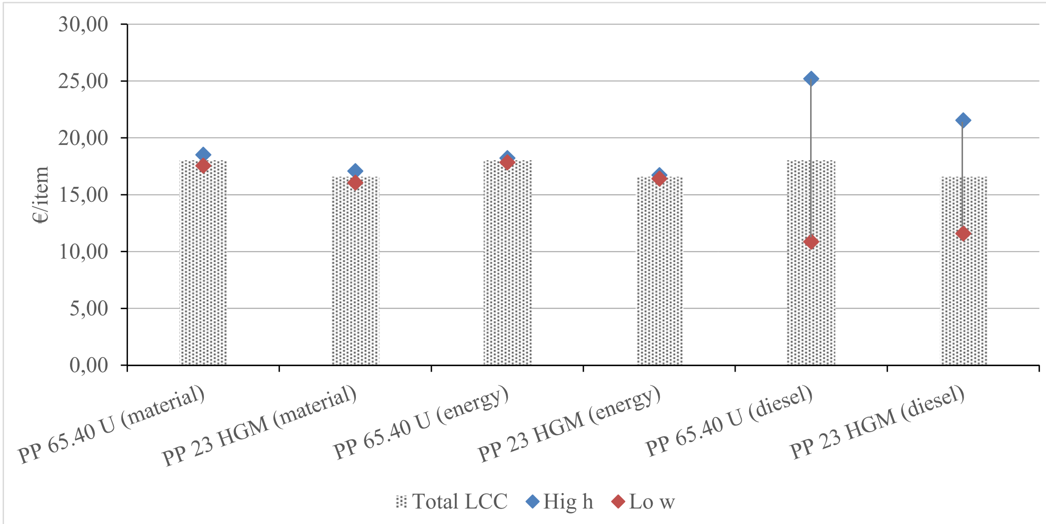

Fig. 8. Cost sensitivity analysis for the two design solutions. The change in component cost is presented for key parameters cost variation (materials, energy and diesel).

phase suggest that the innovative solution is suitable for a mass customization. The innovative solution was found to be preferable also from an economic point of view since beside a higher material cost, it enables a total cost reduction. However, the breakeven analysis shows that the innovative solution is preferable from an environmental point of view more than from the economic one as a break-even point is reached earlier in the vehicle's life span.

From the comparison between the alternative design solutions two evidences arise: the delicate balance between use phase and production phase; the discrepancy between the assessment methods to evaluate the potential impacts during the EoL. A slight trade-off between use phase benefit and raw material phase was found concerning the GWP but it reveals more consistent regarding other environmental indicators. This demonstrates the importance of enlarging the environmental assessment to a diverse set of impact categories, in addition to the CO_2 emissions, to detect the effective advantages of a lightweight solution. In particular the resource depletion was found a challenging issue and this point could have significant implications for future policy planning regarding the automotive sector.

Concerning the second aspect, this study shows that evaluating the EoL phase according to the LCA impact categories could not provide all the necessary information during an early design phase of a component. The EoL phase was found to be negligible if compared with other life cycle phases; moreover the effective consequences of adopting a different material are not always evident. This point confirms the importance of integrating the EoL discussion with elements from the ISO 22682 statements and ELVs targets besides the LCA. Nevertheless, the generic indications of the ISO 22628 could lead to a lack of sensitiveness for two main reasons: the recyclability/recoverability assessments using ISO 22628 do not take into account the loss/efficiency of the recycling/recovery of materials; a clear and systematic way to approach evaluations on the potential disassembly of a component is still missing.

In the present study this gap was faced by taking into account the peculiarity of the available component. However, in the dilemma of achieving the lightweight and the vehicle recyclability target, further research could regard methods for better calculating the direct correlation between a given design solution of a component and the recyclability of the whole vehicle.

Acknowledgments

The authors would like to thank Magneti Marelli S.p.A. for the cooperation. In particular, the authors are very grateful to Mrs. Rubina Riccomagno for her fruitful contribution.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2016.08.079.

References

3M, 2011. Glass Bubble e Risparmio energetico.
3M, 2012. 3M introduces new glass bubble filler for PP and PA systems. Addit. Polym. 2012, 5–6. http://dx.doi.org/10.1016/S0306-3747(12)70088-X.
Andriankaja, H., Bertoluci, G., Millet, P.D., 2009. An approach to define a robust set of environmental tools for car parts manufacturer.
Arai, K., Yamada, K., Hirano, H., Satoh, M., 1998. Process for Producing Inorganic Microspheres. US5849055 A.
Bein, T., Mayer, D., Hagebeuker, L., Bachinger, A., Bassan, D., Pluymers, B., Delogu, M., 2016. Enhanced lightweight design – first results of the FP7 project ENLIGHT. In: Proceedings of 6th Transport Research Arena, April 18–21. Warsaw, Poland.
Berzi, L., Delogu, M., Giorgetti, A., Pierini, M., 2013. On-field investigation and process modelling of End-of-Life Vehicles treatment in the context of Italian craft-type Authorized Treatment Facilities. Waste Manag. 33, 892–906. http://dx.doi.org/10.1016/j.wasman.2012.12.004.
Berzi, L., Delogu, M., Pierini, M., 2016a. Development of driving cycles for electric vehicles in the context of the city of Florence. Transp. Res. Part D Transp. Environ. 47, 299–322.
Berzi, L., Delogu, M., Pierini, M., Romoli, F., 2016b. Evaluation of the end-of-life performance of a hybrid scooter with the application of recyclability and recoverability assessment methods. Resour. Conserv. Recycl 108, 140–155. http://dx.doi.org/10.1016/j.resconrec.2016.01.013.
Bierer, A., Götze, U., Meynerts, L., Sygulla, R., 2015. Integrating life cycle costing and life cycle assessment using extended material flow cost accounting. J. Clean. Prod. Mater. Flow. Cost. Account. 108, 1289–1301. http://dx.doi.org/10.1016/j.jclepro.2014.08.036. Part B.
Cappelli, F., Delogu, M., Pierini, M., Schiavone, F., 2007. Design for disassembly: a methodology for identifying the optimal disassembly sequence. J. Eng. Des. 18 (6), 563–575.
Chatzinikolaou, S.D., Ventikos, N.P., 2015. Holistic framework for studying ship air emissions in a life cycle perspective. Ocean. Eng. http://dx.doi.org/10.1016/j.oceaneng.2015.05.042.
Cichowicz, J., Theotokatos, G., Vassalos, D., 2015. Dynamic energy modelling for ship life-cycle performance assessment. Ocean. Eng. http://dx.doi.org/10.1016/j.oceaneng.2015.05.041.
Das, S., 2011. Life cycle assessment of carbon fiber-reinforced polymer composites. Int. J. Life Cycle Assess. 16, 268–282. http://dx.doi.org/10.1007/s11367-011-0264-z.

Dattilo, C.A., Delogu, M., Berzi, L., Pierini, M., 2016. A sustainability analysis for electric vehicles batteries including aging phenomena. In: Proceedings of the 17th IEEE International Conference on Environment and Electrical Engineering, June 7–10. Florence, Italy.
De Medina, H.V., 2006. Eco-design for materials selection in automobile industry, in: CIRP International Conference on Life Cycle Engineering, 13th, Leuven. Belgium 299–304.
Del Pero, F., Delogu, M., Pierini, M., Bonaffini, D., 2015. Life Cycle Assessment of a heavy metro train. J. Clean. Prod. 87, 787–799. http://dx.doi.org/10.1016/j.jclepro.2014.09.023.
Delogu, M., Del Pero, F., Berzi, L., Pierini, M., Bonaffini, D., 2016a. End-of-life in the Railway Sector: Analysis of Recyclability and Recoverability for Different Vehicle Case Studies (submitted to Waste Management).
Delogu, M., Del Pero, F., Pierini, M., 2016b. Modelling of Use Stage in Lightweight Automotive LCA Perspective: Estimation of Mass-induced Fuel Consumption Reduction for Gasoline Turbocharged Vehicles (submitted to Journal of Cleaner Production).
Delogu, M., Pero, Del, 2015. Life Cycle Assessment of a plastic Air Intake Manifold. Int. J. Life Cycle Assess. 20, 1429–1443. http://dx.doi.org/10.1007/s11367-015-0946-z.
Dhingra, R., Das, S., 2014. Life cycle energy and environmental evaluation of downsized vs. lightweight material automotive engines. J. Clean. Prod. 85, 347–358. http://dx.doi.org/10.1016/j.jclepro.2014.08.107. Special Volume: Making Progress Towards More Sustainable Societies through Lean and Green Initiatives.
EC, 2000. DIRECTIVE 2000/53/EC of the EUROPEAN PARLIAMENTAND of the COUNCIL of 18 Sept 2000 on End-of-life Vehicles.
EC, 2009. REGULATION (EC) No 443/2009 of the EUROPEAN PARLIAMENT and of the COUNCIL of 23 April 2009 Setting Emission Performance Standards for New Passenger Cars as Part of the Community's Integrated Approach to Reduce CO2 Emissions from Light-duty Vehicles.
Ecoinvent, 2016. http://www.ecoinvent.org/ (accessed 25.07.16).
Finkbeiner, M., Hoffmann, R., 2006. Application of Life Cycle Assessment for the Environmental Certificate of the Mercedes-Benz S-Class (7 pp). Int. J. Life Cycle Assess. 11, 240–246. http://dx.doi.org/10.1065/lca2006.05.248.
Froelich, D., Maris, E., Haoues, N., Chemineau, L., Renard, H., Abraham, F., Lassartesses, R., 2007. State of the art of plastic sorting and recycling: Feedback to vehicle design. Min. Eng. 902–912. http://dx.doi.org/10.1016/j.mineng.2007.04.020. Selected papers from Material, Minerals & Metal Ecology '06, Cape Town, South Africa, November 2006 20.
GHK, Bio Intelligence Service, 2006. Costs and Benefits of the ELV Directive – Final Report. A Study to Examine the Benefits of the End of Life Vehicles Directive and the Costs and Benefits of a Revision of the 2015 Targets for Recycling, Re-use and Recovery under the ELV Directive.
Giannouli, M., de Haan, P., Keller, M., Samaras, Z., 2007. Waste from road transport: development of a model to predict waste from end-of-life and operation phases of road vehicles in Europe. J. Clean. Prod. 15, 1169–1182. http://dx.doi.org/10.1016/j.jclepro.2006.05.031. The Automobile Industry & Sustainability.
Go, T.F., Wahab, D.A., Rahman, M.N.A., Ramli, R., Hussain, A., 2012. Genetically optimised disassembly sequence for automotive component reuse. Expert Syst. Appl. 39, 5409–5417. http://dx.doi.org/10.1016/j.eswa.2011.11.044.
Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., Koning, A., de van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H.A., Bruijn de, H., van Duin, R., Huijbregts, M.A.J., 2002. Handbook on Life Cycle Assessment. Operational Guide to the ISO Standards. I: LCA in Perspective. IIa: Guide. IIb: Operational Annex. III: Scientific Background. ISBN 1-4020-0228-9. Kluwer Academic Publishers, Dordrecht, 692 pp.
Hawkins, T.R., Singh, B., Majeau-Bettez, G., Strømman, A.H., 2013. Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles: LCA of Conventional and Electric Vehicles. J. Ind. Ecol. 17, 53–64. http://dx.doi.org/10.1111/j.1530-9290.2012.00532.x.
Heijungs, R., Settanni, E., Guinée, J., 2013. Toward a computational structure for life cycle sustainability analysis: unifying LCA and LCC. Int. J. Life Cycle Assess. 18, 1722–1733. http://dx.doi.org/10.1007/s11367-012-0461-4.
Hunkeler, D., Lichtenvort, K., Rebitzer, G., Ciroth, A., SETAC-Europe (Eds.), 2008. Environmental Life Cycle Costing. SETAC. CRC Press, Pensacola, Fla, Boca Raton.
ISO 14040, 2006. Environmental Management – Life Cycle Assessment – Principles and Framework.
Justel Lozano, D., Espartero Martos, S., García Abaunz, M., Lauroba Izaguirre, N., Muñoz Marzá, C., Vidal, R., 2010. Estudio de desmontabilidad y de fin de vida de la puerta de un C4 Picasso.
Kelly, J.C., Sullivan, J.L., Burnham, A., Elgowainy, A., 2015. Impacts of Vehicle Weight Reduction via Material Substitution on Life-Cycle Greenhouse Gas Emissions. Environ. Sci. Technol. 49, 12535–12542. http://dx.doi.org/10.1021/acs.est.5b03192.
Kim, H.C., Wallington, T.J., 2013a. Life Cycle Assessment of Vehicle Lightweighting: A Physics-Based Model of Mass-Induced Fuel Consumption. Environ. Sci. Technol. 47, 14358–14366. http://dx.doi.org/10.1021/es402954w.
Kim, H.C., Wallington, T.J., 2013b. Life-Cycle Energy and Greenhouse Gas Emission Benefits of Lightweighting in Automobiles: Review and Harmonization. Environ. Sci. Technol. 47, 6089–6097. http://dx.doi.org/10.1021/es3042115.
Koffler, C., 2013. Life cycle assessment of automotive lightweighting through polymers under US boundary conditions. Int. J. Life Cycle Assess. 19, 538–545. http://dx.doi.org/10.1007/s11367-013-0652-7.
Koffler, C., Rohde-Brandenburger, K., 2009. On the calculation of fuel savings through lightweight design in automotive life cycle assessments. Int. J. Life Cycle Assess. 15, 128–135. http://dx.doi.org/10.1007/s11367-009-0127-z.
Kusaka, M., Matsubara, T., Nakao, Y., Yamada, K., 2001. Hollow Glass Microspheres and Method for Producing the Same.
Luz, S.M., Caldeira-Pires, A., Ferrão, P.M.C., 2010. Environmental benefits of substituting talc by sugarcane bagasse fibers as reinforcement in polypropylene composites: Ecodesign and LCA as strategy for automotive components. Resour. Conserv. Recycl 54, 1135–1144. http://dx.doi.org/10.1016/j.resconrec.2010.03.009.
Mayyas, A., Qattawi, A., Omar, M., Shan, D., 2012. Design for sustainability in automotive industry: A comprehensive review. Renew. Sustain. Energy Rev. 16, 1845–1862. http://dx.doi.org/10.1016/j.rser.2012.01.012.
Mayyas, A.T., Qattawi, A., Mayyas, A.R., Omar, M.A., 2012. Life cycle assessment-based selection for a sustainable lightweight body-in-white design. Energy 39, 412–425. http://dx.doi.org/10.1016/j.energy.2011.12.033.
Mercedes-Benz, 2013. Environmental Certificate Mercedes-Benz S-class.
Ragosta, G., Musto, P., Martuscelli, E., Russo, P., Zeloni, L., 2001. Recycling of a plastic car component having a multilayer structure: Morphological and mechanical analysis. J. Mater. Sci. 36, 1231–1241.
Raugei, M., El Fakir, O., Wang, L., Lin, J., Morrey, D., 2014. Life cycle assessment of the potential environmental benefits of a novel hot forming process in automotive manufacturing. J. Clean. Prod. 83, 80–86. http://dx.doi.org/10.1016/j.jclepro.2014.07.037.
Raugei, M., Morrey, D., Hutchinson, A., Winfield, P., 2015a. A coherent life cycle assessment of a range of lightweighting strategies for compact vehicles. J. Clean. Prod. 108 (PA), 1168–1176. http://dx.doi.org/10.1016/j.jclepro.2015.05.100.
Raugei, M., Morrey, D., Hutchinson, A., Winfield, P., 2015b. A coherent life cycle assessment of a range of lightweighting strategies for compact vehicles. J. Clean. Prod. 108, 1168–1176. http://dx.doi.org/10.1016/j.jclepro.2015.05.100. Part A.
Renault, 2011. FLUENCE and FLUENCE Z.E. LIFE CYCLE ASSESSMENT.
Ridge, L., 1997. EUCAR – automotive LCA guidelines – phase 2, Total life cycle conference and exposition. Soc. Automot. Eng. SAE.
Schau, E.M., Traverso, M., Lehmann, A., Finkbeiner, M., 2011. Life Cycle Costing in Sustainability Assessment—A Case Study of Remanufactured Alternators. Sustainability 3, 2268–2288. http://dx.doi.org/10.3390/su3112268.
Schmidt, W.-P., Dahlqvist, E., Finkbeiner, M., Krinke, S., Lazzari, S., Oschmann, D., Pichon, S., Thiel, C., 2004. Life cycle assessment of lightweight and end-of-life scenarios for generic compact class passenger vehicles. Int. J. Life Cycle Assess. 9, 405–416. http://dx.doi.org/10.1007/BF02979084.
Spielmann, M., Scholz, R., 2004. Life Cycle Inventories of Transport Services: Background Data for Freight Transport (10 pp). Int. J. Life Cycle Assess. 10, 85–94. http://dx.doi.org/10.1065/lca2004.10.181.10.
Subic, A., Koopmans, L., 2010. Global green car learning clusters. Int. J. Veh. Des. 53, 36–53. http://dx.doi.org/10.1504/IJVD.2010.032982.
Swarr, T.E., Hunkeler, D., Klöpffer, W., Pesonen, H.-L., Ciroth, A., Brent, A.C., Pagan, R., 2011. Environmental life-cycle costing: a code of practice. Int. J. Life Cycle Assess. 16, 389–391. http://dx.doi.org/10.1007/s11367-011-0287-5.
Tanaka, M., Hirano, H., Yamada, K., 2003. Fine hollow Glass Sphere and Method for Preparing the Same. US6531222 B1.
Tharumarajah, A., Koltun, P., 2007. Is there an environmental advantage of using magnesium components for light-weighting cars? J. Clean. Prod. 15, 1007–1013. http://dx.doi.org/10.1016/j.jclepro.2006.05.022.
Tharumarajah, A., Koltun, P., 2010. Improving environmental performance of magnesium instrument panels. Resour. Conserv. Recycl 54, 1189–1195. http://dx.doi.org/10.1016/j.resconrec.2010.03.014.
Thinkstep, 2016. http://www.gabi-software.com/italy/index/. Accessed 25 July 2016.
Tian, J., Chen, M., 2014. Sustainable design for automotive products: Dismantling and recycling of end-of-life vehicles. Waste Manag. 34, 458–467. http://dx.doi.org/10.1016/j.wasman.2013.11.005.
van Oers, L., de Koning, A., Guinée, J.B., Huppes, G., 2002. Abiotic Resource Depletion in LCA. Improving Characterisation Factors for Abiotic Resource Depletion as Recommended in the New Dutch LCA Handbook.
Volkswagen, A.G., 2012. The Golf. Environmental Commendation – Background Report.
Wesselink, B., Deng, Y., 2009. Sectoral Emission Reduction Potentials and Economic Costs for Climate Change (SERPEC-CC). Summary Report. Ecofys.
Witik, R.A., Payet, J., Michaud, V., Ludwig, C., Månson, J.-A.E., 2011. Assessing the life cycle costs and environmental performance of lightweight materials in automobile applications. Compos. Part Appl. Sci. Manuf. 42, 1694–1709. http://dx.doi.org/10.1016/j.compositesa.2011.07.024.
Yalcin, B., Amos, S.E., 2015. 3-Hollow Glass Microspheres in Thermoplastics. In: Amos, S.E., Yalcin, B. (Eds.), Hollow Glass Microspheres for Plastics, Elastomers, and Adhesives Compounds, Plastics Design Library. William Andrew Publishing, Oxford, pp. 35–105.
Yang, M., Nie, Y.J., Zhu, X.F., 2011. Study on the Application of Low Density SMC for Automotive. Adv. Mater. Res. 179–180, 1042–1046. http://dx.doi.org/10.4028/www.scientific.net/AMR.179-180.1042.
Zanchi, L., Delogu, M., Ierides, M., Vasiliadis, H., 2016a. Life Cycle Assessment and Life Cycle Costing as Supporting Tools for EVs Lightweight Design. In: Setchi, R., Howlett, R.J., Liu, Y., Theobald, P. (Eds.), Sustainable Design and Manufacturing 2016, Smart Innovation, Systems and Technologies. Springer International Publishing, pp. 335–348.
Zanchi, L., Delogu, M., Zamagni, A., Pierini, M., 2016b. Analysis of the main elements affecting social LCA applications: challenges for the automotive sector. Int. J. Life Cycle Assess. http://dx.doi.org/10.1007/s11367-016-1176-8.