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Life cycle assessment of a plastic air intake manifold

Questa è la Versione finale referata (Post print/Accepted manuscript) della seguente pubblicazione:

Original Citation:

Life cycle assessment of a plastic air intake manifold / Delogu, Massimo; Del Pero, Francesco; Romoli, Filippo; Pierini, Marco. - In: THE INTERNATIONAL JOURNAL OF LIFE CYCLE ASSESSMENT. - ISSN 0948-3349. - ELETTRONICO. - 20:(2015), pp. 1429-1443. [10.1007/s11367-015-0946-z]

Availability:

This version is available at: 2158/1010955 since: 2021-03-30T21:32:23Z

Published version:

DOI: 10.1007/s11367-015-0946-z

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06 May 2024

TITLE PAGE

Title: "Life Cycle Assessment of a plastic Air Intake Manifold"

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Abstract:

Purpose

Nowadays some engine components subjected to mechanical stress and high temperature are made of thermoplastic materials. Air Intake Manifold (AIM) is one of these parts. In the past AIM was made of Aluminium or Magnesium alloy while today engine manufacturers prefer to use lighter material such as Nylon reinforced with Glass fibre. The scope of this work is to assess from an environmental point of view the adoption of two alternative thermoplastic materials (Polyamide reinforced with 30% of Glass fibre and Polypropylene reinforced with 35% of Glass fibre) for the construction of a Magneti Marelli® AIM and the introduction in the production stage of new additional design solutions (scraps recycling and brass inserts elimination). The outcome of the paper would contribute both to establish a baseline for comparison with other composite AIMs and improve the knowledge of materials and manufacturing technologies related to the product.

Methods

The study has been performed according to the ISO 14040 standards and the LCA inventory captures the whole AIM Life-Cycle (LC) subdivided in four stages: materials supply, production, use and end-of-Life (EoL). For the LCI data collection, primary data have been provided by AIM manufacturer while available databases have been used as source for secondary data. Unlike previous LCAs regarding AIM, the environmental profile is assessed through a broader range of LCIA impact categories, referred to the CML 2001 method.

Results

The results show that for both the Polyamide composite and the Polypropylene composite AIM the most influential LC stages are use and materials supply. Such outcome is due to the considerable quantity of fuel consumed during the whole LC and the energy/resources consumption involved by the raw materials extraction and production processes. The substitution of Polyamide composite with Polypropylene composite lowers the environmental impacts for all the categories and for each stage of the AIM LC. The change of material involves a remarkable increase of the use stage quota, totally to the detriment of materials supply, with no notable mutation of Production and EoL contributions. The introduction of scraps recycling and brass inserts elimination entails no significant impact reduction for all the categories with the only exception of ADPe.

Conclusions

The substitution of Polyamide composite with Polypropylene composite involves considerable reduction of the AIM LC impact while the introduction of scraps recycling and brass inserts elimination entails negligible effects.

Keywords:

Life Cycle Assessment - Air Intake Manifold – Vehicle - Environmental Impact- Eco design - Energy consumption

1. Introduction

1.1. Introduction to AIM design and production issues

The use of plastic material in the automotive sector, in particular its application for engine parts, started in the '70s for many advantageous aspects: the automotive component results lighter, noise suppressive, rustproof, and also economically convenient if compared to the traditional metallic ones. Considering for example the nylon thermoplastic polymer (the most used in the automotive industry), in 1960 the average quantity used per car was 0.18 kg, while in 1995 it reached 4 kg (Carlson and Nelson, 2003). Today 12% - 15% of the mass of a modern car is made of plastic (PlasticsEurope, 2010).

The Air Intake Manifold (AIM) is used in the intake system of an engine with the function to distribute the intake air to the individual engine cylinders. In the past AIM was usually made of Aluminium or Magnesium alloys and produced with a sand-cast process or alternatively with a multi-tube brazed process. At the beginning of the '70s Porsche and Ford introduced plastic AIM using a simple shape and structure, and in 1989 BASF created the melt-core moulding method (Mukawa et al., 1996). Since AIM has to support the throttle body's weight, and eventually the increase of pressure due to the presence of a turbo charger, from the very first applications the thermoplastic polymers were always reinforced using a percentage of fibrous glass (Mathew and Wiebeck, 1999; Mukawa et al., 1996).
At the end of the '90s the automotive market of plastic AIM was growing, and in 2000 market studies predicted that in a few years at least 50% of all the AIMs would be made of thermoplastic polymers (Palmer et al., 1996) (Edwards and Daly, 1999). To date plastic composites for AIMs production has become a material widely used by several car manufacturers all around the world.

Introduction of thermoplastic polymers in AIM production led to significant benefits (Thatcher et al., 1992; Mathew and Wiebeck, 1999) which today are still valid (Klein and Wiese, 2011; Defosse, 2009):

- weight reduction: the plastic AIM has in general less mass than the equivalent metallic one;
- cost reduction of the entire AIM LC;
- noise reduction, by means of vibration-absorbing effect of the plastic material;
- improvement of engine performance, estimated about 2% higher than the equivalent Aluminium manifold. This is due to both the smooth internal surface of tracts/plenum and the lower air charge temperatures for thermal insulation effect.

At the same time the introduction of plastic materials in AIM design process involved many important changes in engine technology, leading to the redesign of the overall engine (Schramm, 1992). The design of the whole intake system, consisting of intake manifold together with air filter, resonators and air hoses, has to be developed considering the interaction of the entire system, including the gas dynamics, acoustics and other aspects (Paffrath et al., 1999). Computer-Aided Engineering (CAE) methodologies are consequently necessary in order to take into account these multiple aspects (Tanaka and Kitagawa, 2007). In particular, Noise, Vibration, and Harshness (NVH) have been investigated by many authors (Dimeo et al., 2012; Battistoni et al., 2006; Hu et al., 2003; Siavoshani et al., 2001; Novak et al., 2001; Sievewright, 2000; Kraft, 2000; Pricken, 1999; Kraft et al., 1995; LEE, 1998; Sievewright, 1998; Capitani et al., 1999, 2000, 1998).
The various moulding methodologies to produce a plastic AIM are listed below:

- lost core method: it involves the use of a core made of low melting-point alloy (generally Bi/Sn) that is set into the injection moulding machine. After the injection process the core is melted in the oil bath and removed using an electromagnetic induction heating system. This method has however some negative aspects, such as toxicity, tendency to entrap metallic parts into the AIM and high costs (Todd and Pascoe, 1987);
- part welding method: two or more parts are first prepared separately by injection moulding and then joined together by the use of a vibration welding process (Bates et al., 2004; Lee et al., 1998; Nelson, 1995). A positive aspect of the method is the relatively low cost of production. On the other side some possible drawbacks are the limited design freedom and the reliability of the welding, that may be highly stressed in case of "backfires" and associated rapid strain rates (Zucchelli et al., 2009; Kondapalli and Sirani, 2000; Caskey and Daly, 1998);

- rotating core method: in this case the core is removed while it is being rotated, thus limiting the design possibilities of AIM (Mukawa et al., 1996);
- combined method of blow moulding and injection moulding: developed by Fuji Heavy Industries Ltd. (Mukawa et al., 1996), the method combines low-pressure moulding and blow moulding;
- other methods are the Die Rotary Injection (DRI) process (Yamaguchi, 2000), the Thermoforming Process (Mallick and Daly, 2000), and the Adhesive Shell Bonding (Hickman and Schumacher, 2005).

Plastic AIMs were initially used for the gasoline engines and only in the '90s its application was extended to the diesel engines. The first application on a diesel was made by Ford on the 1.6L Zeta engine (Thatcher et al., 1992) and it comprehended the emission control system known as Exhaust Gas Recirculation (EGR). Considering that EGR system has to cope with a high gas temperature, precautions should be taken in order to protect the manifold using a thermal isolator as an interface between the high temperature EGR outlet tube and the thermoplastic manifold (Bauhof and Castle, 1993). Successful design strongly depends on the correct prediction of temperature loads and at this purpose CFD calculation represents a valuable tool (Wehr et al., 2002).

1.2. LCA of AIM and other sustainability aspects

Environmental considerations and comparisons regarding AIMs differing for construction material and/or production processes started in the 90's and they were based mainly on Life Cycle Assessment (LCA) analyses.
The first study (Schuckert et al., 1993) was performed for Ford and compares an Aluminium AIM to one made of Zytel®, a thermoplastic polymer obtained with Nylon 66 reinforced with 30% of Glass fibres and commercialized by Du Pont®. The results indicate that the Nylon alternative involves notable advantages from an environmental point of view, especially in terms of energy and material consumption, greenhouse gases, and consumed landfill volume; only the contribution related to acidification results approximately equal for the two materials.
A successive LCA study (Kar and Keoleian, 1996) compares a prototype sand-cast 2.0 l Aluminium AIM for the 1995 Ford Contour and an equivalent AIM made of multi-tube brazed Aluminium for the 1995 Ford Escort 1.9 l. The results show better environmental performance of the multi-tube brazed manifold with regard to energy consumption, air emissions, and waterborne waste while solid wastes result lower for the sand-cast manifold. The study comprehends also a Life Cycle Cost (LCC) analysis of both processes, showing almost identical results.
Keoleian and Kar expanded their work by another LCA on AIM first published as an U.S. Environmental Protection Agency (US EPA) report (Keoleian and Kar, 1999), and then as a scientific article (Keoleian and Kar, 2003). The research was carried out in collaboration with the University of Michigan, US EPA, and Ford and treated with three AIM design alternatives: a sand cast Aluminium, a brazed Aluminium tubular, and a Nylon composite (this latter made with a lost-core process). LC inventory shows that the sand cast Aluminium manifold consumes bigger quantity of energy compared to the tubular brazed Aluminium and Nylon composite AIMs. The study was completed by a LCC analysis estimating Ford manufacturing costs, customer gasoline costs, and EoL management costs. Nylon composite AIM has the highest estimated manufacturing costs (due to the lost-core moulding process) but the least use phase gasoline costs.
In a subsequent LCA (Spitzley and Keoleian, 2001) performed in collaboration with the University of Michigan, US EPA and Ford, three design alternatives for the lower plenum of the AIM of a 5.4L F-250 truck engine were compared. Such alternatives are:

- sand cast Aluminium;
- lost core moulded Nylon composite;
- vibration welded Nylon composite.

The study includes both a Life Cycle Inventory (LCI) and a LCC analysis in addition to an evaluation of product performance and environmental regulatory/policy. The LCI shows that the vibration welded composite consumes less LC energy compared to both the lost core composite and the sand cast Aluminium AIM. The study investigates also some recycling scenarios for Aluminium and Nylon: utilizing available technology for incorporating 30% post-consumer Nylon into the welded composite AIM would reduce the LC energy consumption by 4%. LCC results indicate that the vibration welded composite is the cheapest alternative: it costs 64% less than the lost core composite which in turn is 20% less expensive than the sand cast Aluminium AIM.

Considering other recent environmental improvements related to plastic AIM, in the Brazilian market (Villalva et al., 2012) it has been developed an AIM using the Technyl ECO®, a new chemically recycled material recuperated from yarn production process. The use of this material allows to achieve a reduction of 4.3 kg of CO_2 equivalent per 1 kg of matrix produced; moreover it can replace the current Polyamide 6.6 reinforced with 30% of Glass Fibre, having the same formulation and analogue mechanical resistance.
Another recent alternative solution to the use of Polyamide for the realisation of AIM is represented by Polypropylene reinforced with 35% of Glass fibres. This material was adopted in 2010 by Volkswagen Group®, the first automotive OEM to switch from Polyamide to Polypropylene. The advantages of using Polypropylene reinforced with Glass fibres are a long-term high heat and chemical resistance, vibration/fatigue resistance and a larger range of operating temperature (-40°C - +120°C). Moreover, this material allows to use the same manufacturing processes and shows better acoustic performance with a lower density, determining a mass reduction of about 15% with regard to Polyamide.

From the review of existing literature regarding environmental studies of AIMs, it can be concluded that:

- the analyses are dated; moreover no LCA studies on AIM made with Polypropylene are available;
- LCA studies focus on a single or limited set of environmental indicators, with energy consumption and GHG emissions being the most common.

This paper treats a comparative LCA of different case studies for an AIM manufactured by Magneti Marelli® (MM) (model "CAB FIRE 317"), and installed on a specific model of compact car equipped with a naturally aspirated gasoline engine. In comparison to existing studies, this work examines a broader range of impacts to both human and ecosystems health using primary data supplied by vehicle manufacturers whenever possible to reduce the uncertainty of results.

2. Materials and method

The LCA of MM AIM has been performed according to the ISO standards. In the following paragraphs the study is described in detail step by step.

2.1. Goal of the study

2.1.1. Intended application

This study is intended to provide support in the development of the AIM model "CAB FIRE 317" produced by the commissioner (MM).

2.1.2. Reasons for carrying out the study

The motivations of this study are related to the company culture, with the objective to:

- improve the knowledge, from an environmental point of view, of materials and manufacturing technologies related to the AIM;
- establish a baseline for comparison with other composite AIMs, differing each other for raw materials and/or technology solutions;
- identify the largest contributors that determine environmental impacts, resources consumptions and human health issues;
- avoid the shift of problems between different impacts categories and between LC stages;
- evaluate the primary energy (from non-renewable and renewable resources) that is required in the various LC stages.

2.1.3. Intended audience

The intended group of audience for which this study has been addressed is an internal group of the Company, mainly constituted by members of the Powertrain and Innovation business lines. Parallel to this article, a specific internal report has been prepared, including normalization and weighting, that are vice versa excluded from the paper.

2.1.4. Intended for comparative assertions

This study has not been intended for comparisons with AIMs produced by competitors, but only for assessing different AIM solutions which differ for raw materials and/or design options.

The final objectives of this comparative LCA is to assess the environmental effects due to:

- adoption of two alternative thermoplastic materials for the construction of the AIM: Polyamide 6 reinforced with 30% of Glass fibre (Polyamide composite) and Polypropylene reinforced with 35% of Glass fibre (Polypropylene composite);
- introduction in the production stage of new additional design solutions: Scraps recycling and Brass inserts elimination.

2.2. Scope of the study

2.2.1. Description of AIM and case studies

The AIM ensures the optimal filling of the engine cylinders with a suitable mass of combustive agent and carries out the function of integrating control systems related to fuel supply, fuel anti-evaporation and engine operation point. Basically, the AIM consists of a volume of thermoplastic material with high thermal and mechanical resistance, composed by three parts made by injection moulding technology and joined by vibration welding:

- Central Body
- Lower Cover
- Upper Cover

The other components that complete the AIM are:

- Throttle body gasket
- Runner gasket
- Throttle body brass inserts
- Filter insert
- Compression limiters

Table A in the SI appendix reports the main technical features of the AIM configuration considered as reference case study while Figure A in the SI appendix shows an image of the whole system.

In addition to the reference case study, five alternative case studies have been considered. Such alternatives are obtained by single or simultaneous application to the reference case study of the following design solutions:

- substitution of the reference raw material (Polyamide composite) with Polypropylene composite;
- introduction in the Production stage of recycling of polymeric scraps deriving from manufacturing processes (injection moulding and vibration welding) in order to partially substitute virgin raw material;
- application of an alternative AIM design layout which involves brass inserts elimination.

Table B in the SI appendix reports the mass of the plastic components in the Polypropylene AIM case studies while Table C summarises all case studies compared in the analysis.

2.2.2. Functions of the product system

As previously explained in detail in paragraph 1.1, AIM is used in the intake system of an engine and its function is to distribute the intake air to the individual engine cylinders.

2.2.3. Functional Unit

The Functional Unit (FU) is the production of the MM AIM model “CAB FIRE 317”, its use on a car for 150.000 km, and its End-of-Life (EoL).

2.2.4. Application and system boundaries

Depending on the goal and scope of the study, the system boundaries define the Process Units (PUs) to be included in the analysed system. According to the “from cradle to grave” approach, the LC stages taken into account are:

- Materials supply
- Production
- Use
- EoL

Table D in the SI appendix reports AIM LC stages subdivided in PUs and single processes.

2.3. Life Cycle Inventory (LCI)

Collection of primary data has been performed for all PUs that compose AIM LC and the gathered data come directly from real operators of processes. The database version 6.106 of software GaBi (PE International, 2013) has been used as source for secondary data.

2.3.1. Materials supply

For PU “Raw materials extraction and production”, data collection consists of determination of typology and quantity of materials constituting the AIM. Table A in the SI appendix reports LCI data for PU “Raw materials extraction and production”.

For PU “Raw materials transportations”, data collection involves the determination of truck type, travelled distance, and route composition (highway and urban) characterising transportation of materials from suppliers facilities to MM plants. Table E in the SI appendix summarises data collection for PU “Raw materials transportations”.

2.3.2. Production

For PU “Manufacturing”, data collection consists of the quantification of material and energy flows related to the production of a single AIM and it has been conducted by direct measurements on MM processes (reference year for the measurements 2012). Data collection has been performed for all the processes included in the PU “Manufacturing”. In order to consider also the environmental impact due to the production of the sample products destined to destructive quality tests, material and energy flows have been adequately increased.

Data collection for PU “Internal transportations” consists of the determination of truck type, travelled distance, and route composition (highway and urban). Table F in the SI appendix reports data collection for PU “Internal transportations”, referring to transportations performed between MM plants in the Production stage.

Following assumptions have been considered to collect secondary data regarding the production of thermoplastic raw materials (Polyamide and Polypropylene):

- Polyamide production: “PA6 (IT)” GaBi6 process has been used because of its geographical pertinence for the present case study (Italy);
- Polypropylene production: “PP mix (DE)” GaBi6 process has been used because it was the best available option in terms of data update and representation of average production processes based on benchmark panels;
- Production of Polyamide and Polypropylene composite has been modelled by summing contributions of production processes of both plastic matrix and reinforcement fibres. Percentages referring to single interventions of matrix and fibres are the following:
    - Polyamide composite: 70% Polyamide production and 30% Glass fibres production;
    - Polypropylene composite: 65% Polypropylene production and 35% Glass fibres production.

2.3.3. Use

For the use stage data collection involves the determination of vehicle consumption and emissions attributable to the AIM. At this scope an analytical model is used.

The amount of fuel consumed during the entire vehicle life-time attributable to the AIM (*$fuel_{AIM}$*) is assumed equal to the mass-induced energy consumption of the component and is determined through the approach proposed by Koffler and Rohde-Branderburger (2010). Such approach is based on the mass-induced fuel consumption starting from

- the amount of work necessary to move 100 kg on a specific driving cycle
- the differential efficiency of the internal combustion engine.

$fuel_{AIM}$ is calculated through the following equation:

$$fuel_{AIM} = 0{,}15 * \frac{mass_{AIM}}{100} * \frac{use_{km}}{100}$$

Where:

$fuel_{AIM}$ = Fuel consumption during the entire vehicle life-time attributable to the AIM [l];

0,15 [l/100km*100kg] = Mass-induced fuel consumption for a naturally aspirated gasoline car through the New European Driving Cycle (NEDC);

$mass_{AIM}$ = Mass of the AIM [kg];

use_{km} = Travelled kilometres during vehicle life-time [km].

The amount of emissions during the entire vehicle life-time attributable to the AIM is calculated by the following equation:

$$emiss_i = emiss_{i\ km} * use_{km} * \frac{100 * fuel_{AIM}}{fuel_{vehicle} *\ use_{km}}$$

Where:

$emiss_i$ = Emissions of pollutant *i* during the entire vehicle life-time attributable to the AIM [g];

$emiss_{i\ km}$ = Vehicle per-kilometre emission of pollutant *i* [g/km];

$fuel_{vehicle}$ = Vehicle per-kilometre fuel consumption [l/100km].

As the model scales the emissions linearly with the fuel consumption attributable to the AIM, only the usage emissions which directly depend on the amount of fuel consumption (CO_2 and SO_2) are considered in the assessment.

For the modelling of the use stage a reference vehicle with the same technical characteristics of the car on which the AIM is installed has been chosen: Table G in the SI appendix shows its use phase technical data.

2.3.4. End-of-Life

The study on recovery of plastic from End-of-Life Vehicles (ELV) conducted by Jenseit (Jenseit et al., 2003) highlights that accessibility is a key point for the removal of AIM from engine compartment. Mechanical recycling is surely the most “environmentally friendly” EoL treatment, especially if compared to waste incineration or landfilling. The decision whether mechanical recycling should be applied depends on dismantling time and AIM mass. At this purpose, considering the on-field investigation of ELV treatment in the context of Italian craft-type Authorized Treatment Facilities (Berzi et al., 2013), it has been assumed that the most likely scenario is that the AIM remains on the ELV. Later the AIM is led to the shredding and milling processes, it becomes “fluff” and finally it is landfilled. In order to evaluate the energy consumption due to the AIM shredding and milling, it has been assumed an average plastic granulating process. Since the plastic grains obtained by an average granulating process are characterised by smaller particle size than the car fluff, such assumption conservatively overestimates the energy used for shredding and milling. Finally, car fluff disposal has been properly modelled as landfilling.

2.3.5. Cut off criteria

Table H in the SI appendix summarises AIM LC processes that have been cut off from the study and motivations of exclusion. The exclusions concern technologies that have negligible influence (less than 1%) on the total impact of LC stage in which they are located.

2.3.6. Data Quality

Where possible processes data (materials and energy flows) have been collected as primary data by direct measurements on industrial processes. In other cases secondary data from GaBi6 database have been used. Table I and Table J in the SI appendix summarise information referring to primary and secondary data respectively.

2.4. Life Cycle Impact assessment (LCIA) method

Considering the Goal of the study (paragraph 2.1.2), the mid-score method CML 2001 (University of Leiden, 2001) has been chosen as it is scientifically valid and widely accepted. It includes following impact categories:

- Abiotic Depletion Potential (ADP elements)
- Abiotic Depletion Potential (ADP fossil)
- Acidification Potential (AP)
- Eutrophication Potential (EP)
- Freshwater Aquatic EcoTox Pot. (FAETP)
- Global Warming Potential (GWP)
- Human Toxicity Potential (HTP)
- Marine Aquatic EcoTox Pot. (MAETP)
- Ozone Layer Depletion Potential (ODP)
- Phot. Ozone Creation Pot. (POCP)
- Terrestric Ecotoxicity Potential (TETP inf.)

Additionally to the CML 2001 impact categories, also the Primary Energy Demand (PED) from Renewable and Non-renewable resources has been considered.

3. LCIA results

Table K and Table L in the SI appendix report LCIA results for Polyamide composite AIM (reference case study) and Polypropylene composite AIM, expressed both per total LC and per single LC stage. Production stage is split in PUs “Manufacturing” and “Internal transportations” to explicitly report the contributions of the PUs performed inside MM plants.

Figure 1 reports LCIA results for all case studies expressed with respect to the entire LC; data are quantified as % of impact of Polyamide composite AIM.

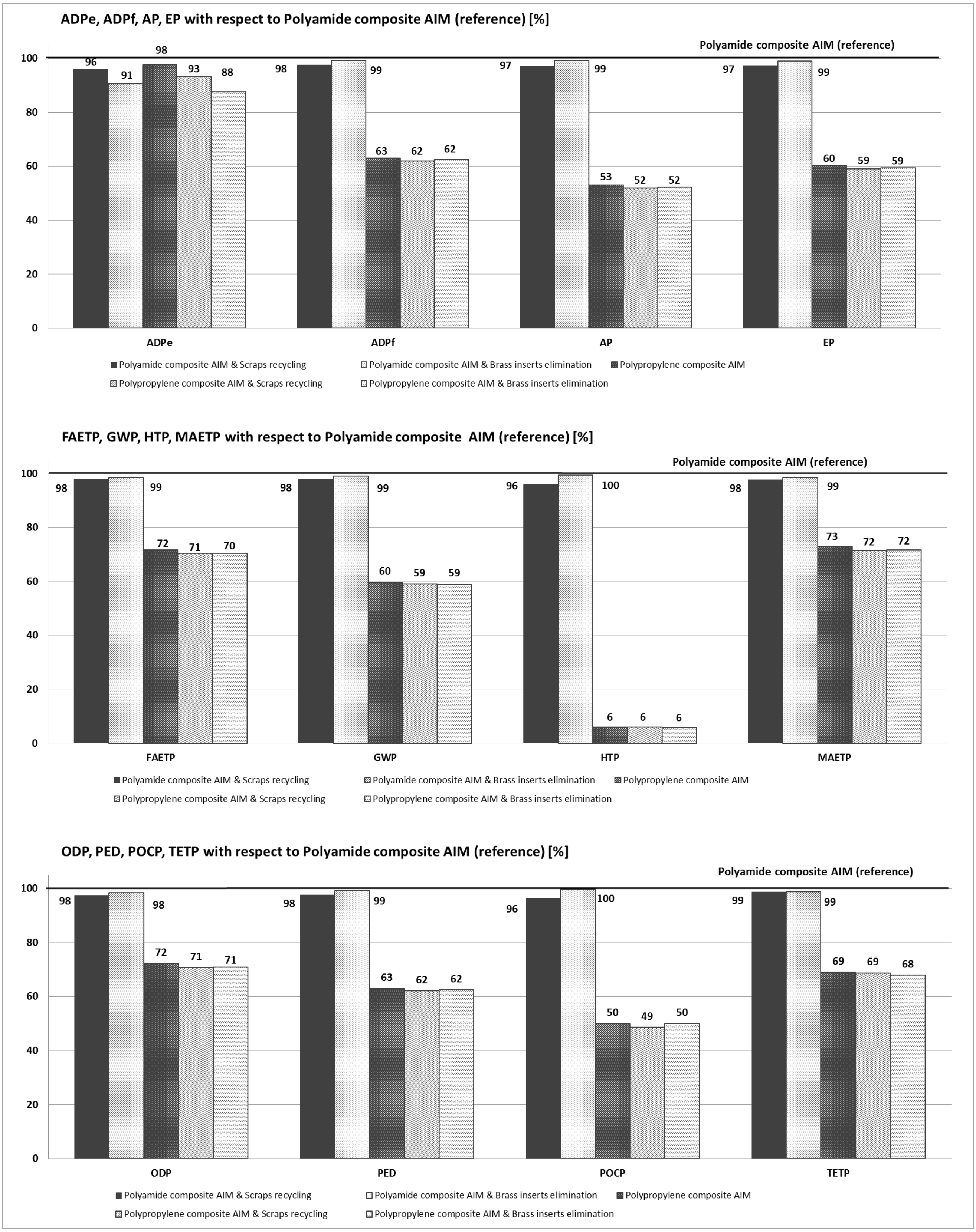

Figure 1 - Complete set of LCIA results of all cases; data are expressed as % of impact of Polyamide composite AIM (reference)

4. Discussion

Results are compared and interpreted. Comments are divided in five sections:

- Contribution analysis by LC stage of impact

- Effect of changing construction material for the AIM plastic elements
- Effect of scraps recycling introduction
- Effect of brass inserts elimination
- Sensitivity analysis

4.1. Contribution analysis by LC stage of impact

Figure 2 reports contribution analysis by LC stage of impact for the Polyamide composite AIM (reference case study). The most influential LC stages are Materials supply and Use: interventions of such stages account for more than 90% for eight of the eleven impact categories. Such outcome is due to:

- the energy and resources consumption involved by PU "Raw materials extraction and production" (for the Materials supply stage);
- the considerable quantity of consumed fuel and emissions during the whole operation (for the Use stage).

Interventions of production stage do not exceed 13% for all the impact categories with the exception of ODP whose quota (22%) is totally attributable to PU "Manufacturing". EoL contribution is lower than 10% for all the categories.

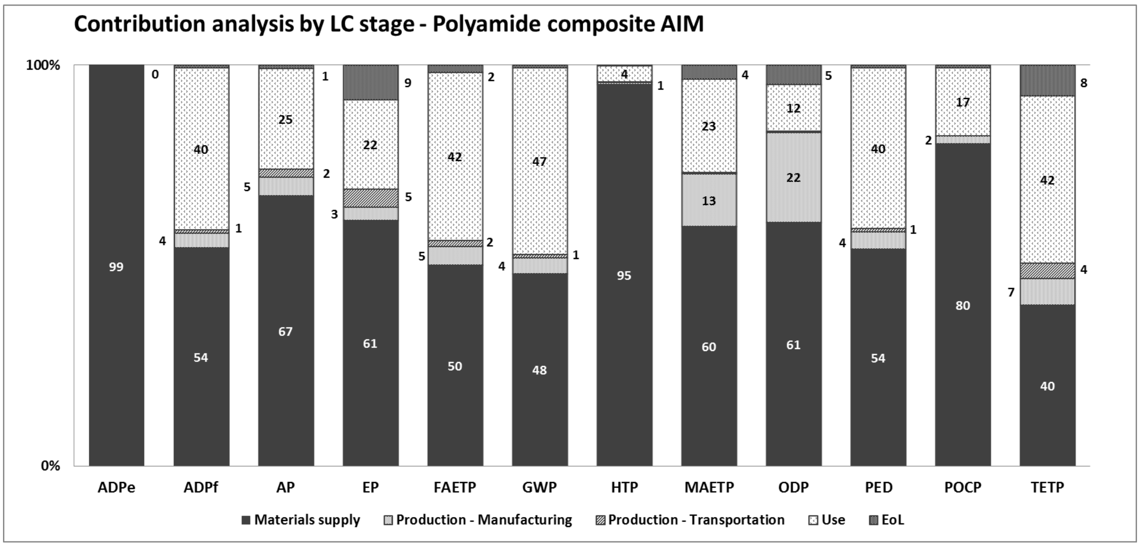

Figure 2 - Contribution analysis by LC stage for Polyamide composite AIM (reference)

4.2. Effect of changing plastic material for AIM

The change of material from Polyamide composite to Polypropylene composite has involved a considerable reduction of the AIM LC impacts. Figure 3 reports impacts reduction achieved by Polypropylene composite AIM expressed as percentage of Polyamide composite AIM (reference). The highest impact reduction (94%) regards HTP while for ADP_e the effect is almost null: the other categories show reductions included in the range 27% - 50%.

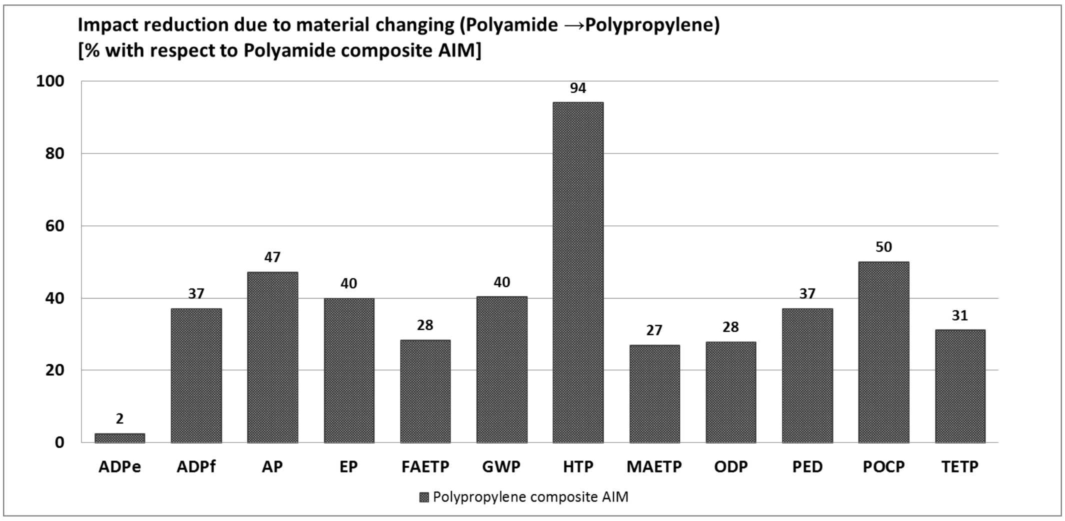

Figure 3 - LCIA results for Polypropylene composite AIM expressed as % of Polyamide composite AIM (reference)

Figure 4 reports contribution analysis by LC stage of impact of Polypropylene composite AIM. The comparison with data reported in Figure 2 evidences that change of material involves a remarkable increase (10% - 20%) of the use stage quota for the majority of impact categories, totally to the detriment of materials supply. The only exceptions are ADP_e and HTP. For ADP_e contributions of material supply and use remain unchanged (99% attributable to PU "Raw materials extraction and production" for both cases). For HTP use stage intervention grows up to 57% causing a drastic reduction of material supply quota (32%) while production contribution reaches 10%. The grow of use stage quota is explainable with the minor energy intensity of Polypropylene composite raw materials extraction and production processes despite the lower use stage impact involved by a lower AIM mass. Production and EoL contributions show no remarkable variations due to change of material (maximum increase for both categories does not exceed 3%).

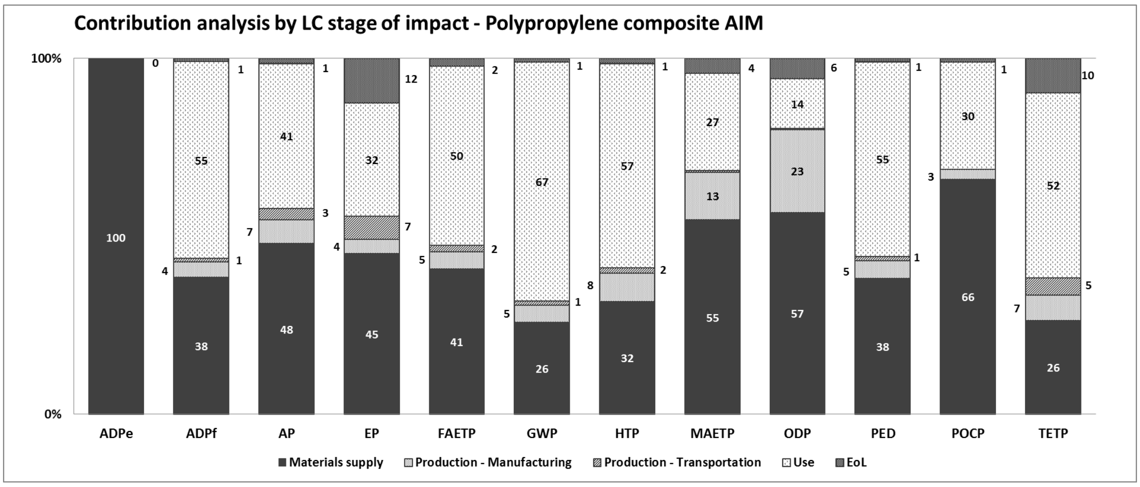

Figure 4 - Contribution analysis by LC stage for Polypropylene composite AIM

4.3. Effect of scraps recycling introduction

Figure 5 reports impact reduction achieved by introduction of plastic scraps recycling for both Polyamide composite and Polypropylene composite AIM. Data referring to Polyamide composite AIM & scraps recycling are expressed as percentage of impact of Polyamide composite AIM; similarly data referring to Polypropylene composite AIM & scraps recycling are expressed as percentage of the impact of Polypropylene composite AIM. The impact reduction is negligible for both cases. For Polyamide composite AIM & scraps recycling, the highest impact reduction (about 4%) regards ADP_e, HTP and POCP while for all the other categories decrease is below 3 % till a minimum of 1.2% for TETP. For Polypropylene composite AIM & scraps recycling impact reductions are lower for all categories with the exception of ADP_e (4,4%).

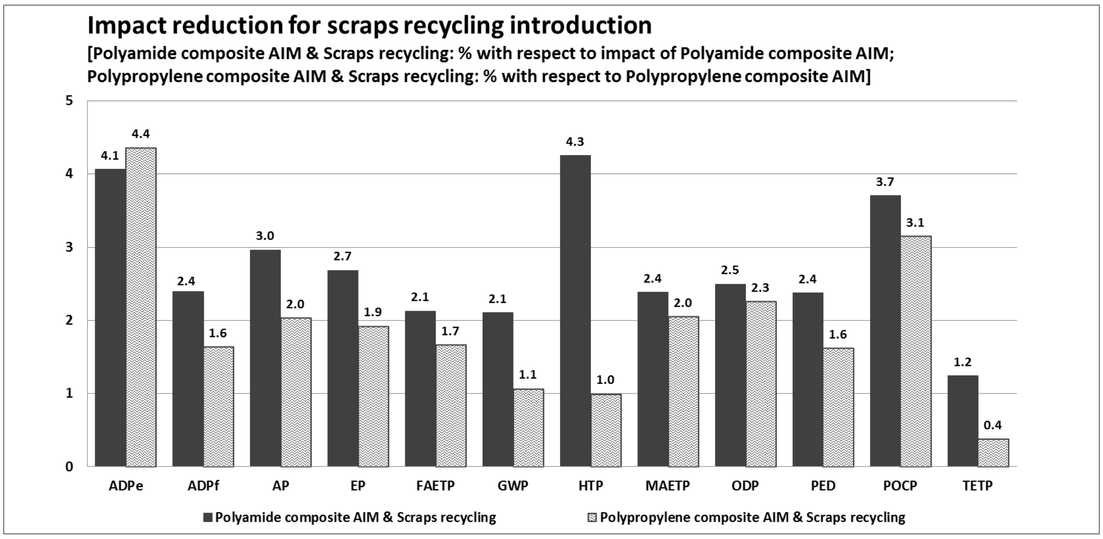

Figure 5 - Impact reduction for introduction of scraps recycling [Polyamide composite & scraps recycling: % with respect to impact of Polyamide composite AIM; Polypropylene composite AIM & scraps recycling: % with respect to impact of Polypropylene composite AIM]

4.4. Effect of brass inserts elimination

Figure 6 reports impact reduction achieved by elimination of brass inserts for both Polyamide composite AIM and Polypropylene composite AIM. Data referring to Polyamide composite AIM & brass inserts elimination are expressed as percentage of impact of Polyamide composite AIM; similarly data referring to Polypropylene composite AIM & brass inserts elimination are expressed as percentage of impact of Polypropylene composite AIM. The effect is a low reduction for all impact categories. Decreases do not exceed 3% with the exception of ADP_e for which reduction is about 10% for both cases.

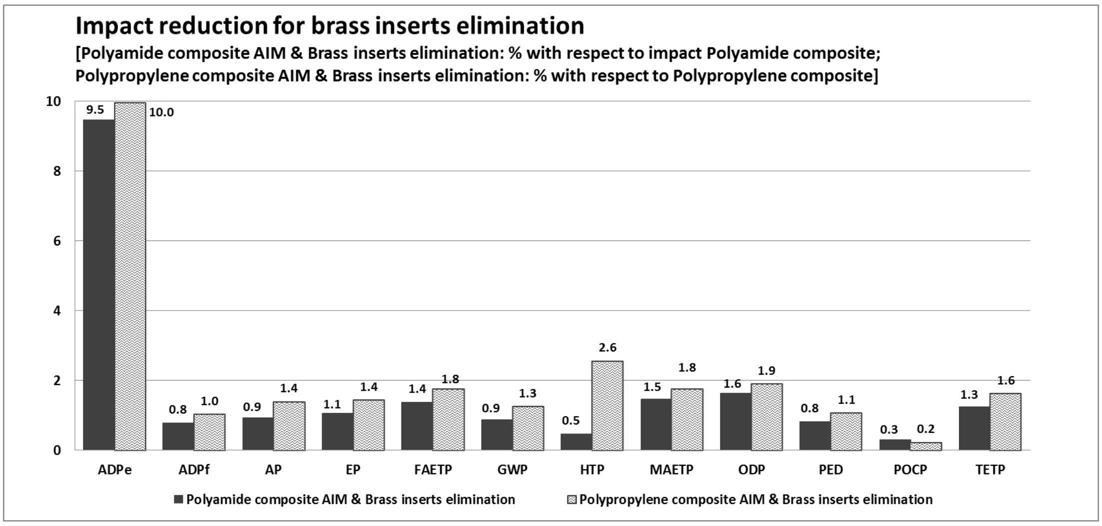

Figure 6 - Impact reduction for brass inserts elimination [Polyamide composite AIM & brass inserts elimination: % with respect to impact of Polyamide composite AIM; Polypropylene composite AIM & brass inserts elimination: % with respect to Polypropylene composite]

4.5. Sensitivity Analysis

Considering that use stage represents a considerable quota of total LC impact for the major part of categories, a sensitivity analysis based on vehicle LC mileage has been performed. In parallel to the standard LC mileage scenario of 150000 km, two additional scenarios have been evaluated:

- 100000 km LC mileage
- 200000 km LC mileage

Figure 7 and Figure 8 show the percentage impacts for 100000 and 200000 km LC mileages with regard to the reference scenario.

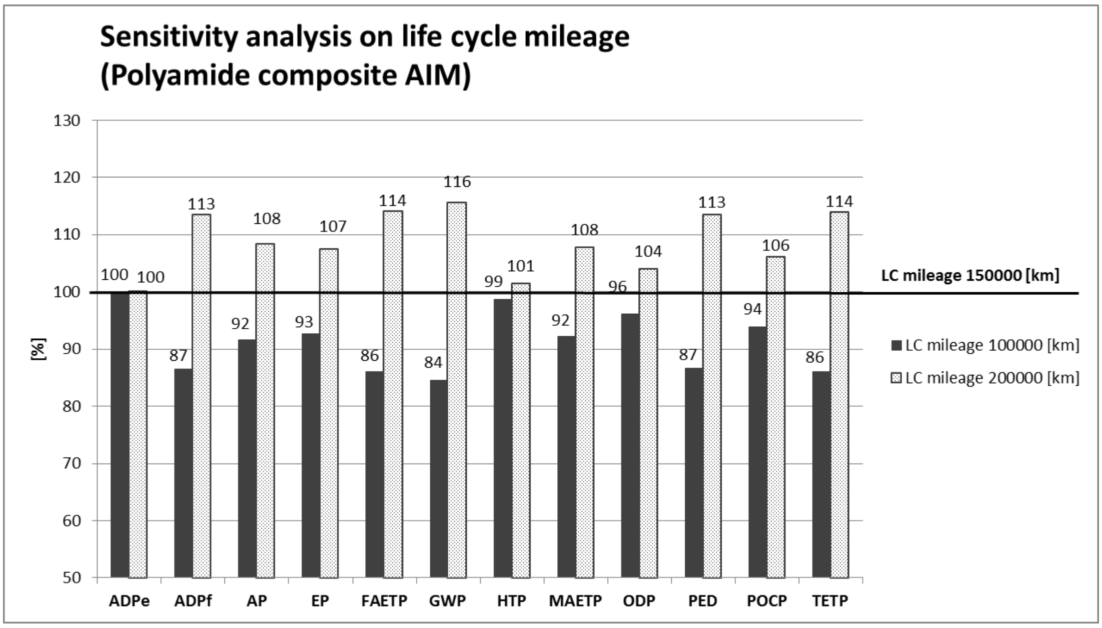

Figure 7 – Sensitivity analysis on LC mileage (Polyamide composite AIM)

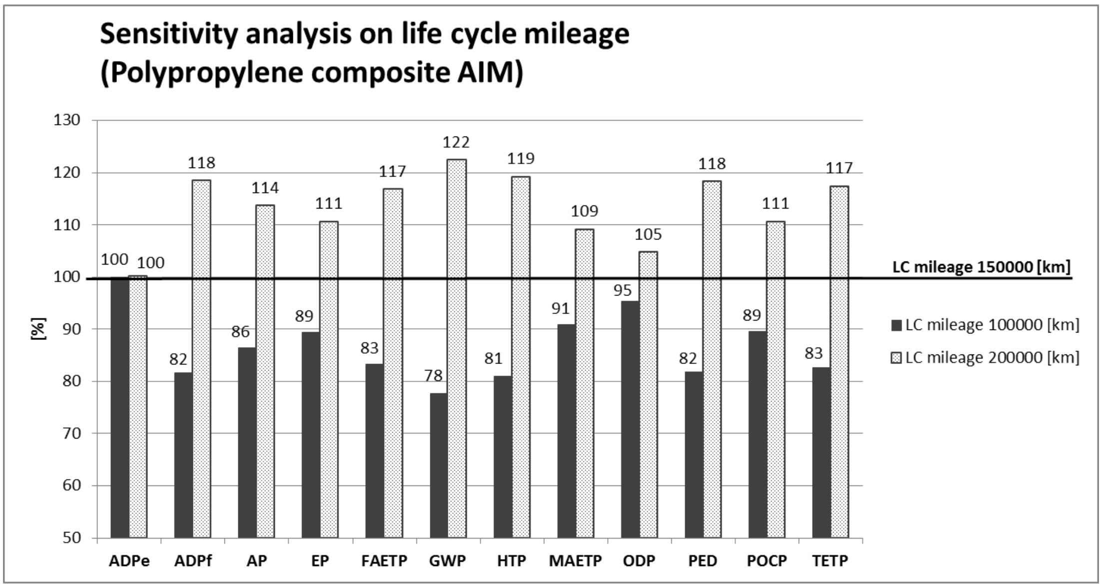

Figure 8 - Sensitivity analysis on LC mileage (Polypropylene composite AIM)

ADP_e is mainly invariant with respect to LC mileage change (being it related to the raw material production stages) while other impact categories are subjected to variations of about ± 20%.

Figure 9 and Figure 10 show the percentage impacts of Polypropylene composite AIM with respect to Polyamide composite AIM for 100000 km and 200000 km LC mileage respectively.

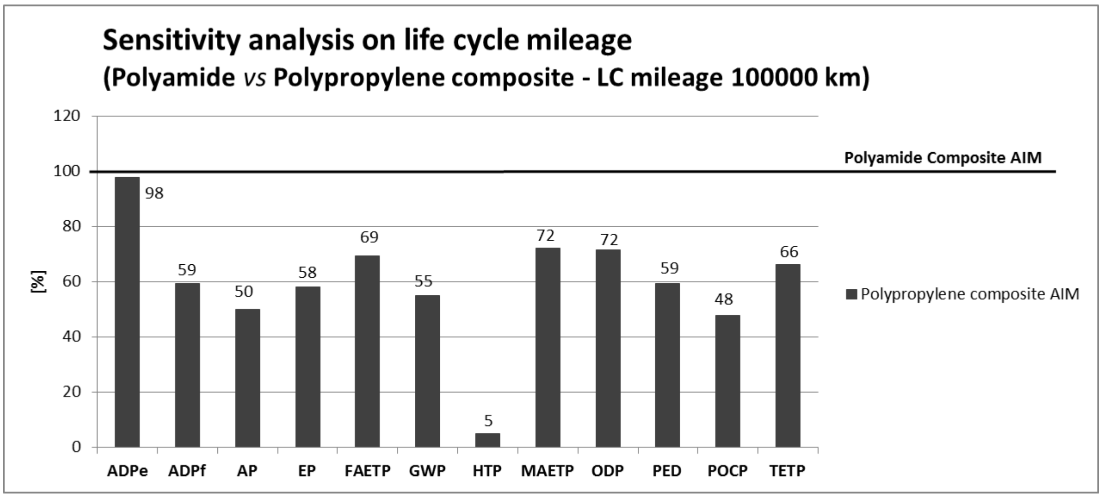

Figure 9 - Sensitivity analysis on LC mileage (Polyamide vs Polypropylene composite AIM, LC mileage 100000 km)

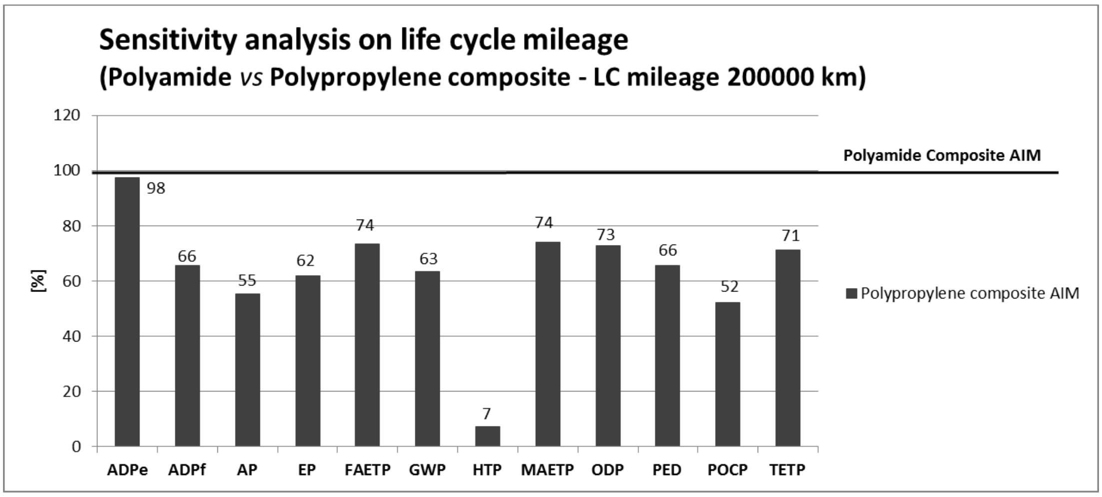

Figure 10 - Sensitivity analysis on LC mileage (Polyamide vs Polypropylene composite AIM, LC mileage 200000 km)

The Polypropylene composite AIM involves impact reduction for all the considered LC mileage scenarios. Figure 11 shows GWP of Polyamide and Polypropylene composite AIMs in function of LC mileage: both functions are represented by lines nearly parallel, with a slightly reduced slope for Polypropylene composite AIM. The absence of an intersection between the two lines confirms the advantages of the Polypropylene composite AIM for whichever LC mileage.

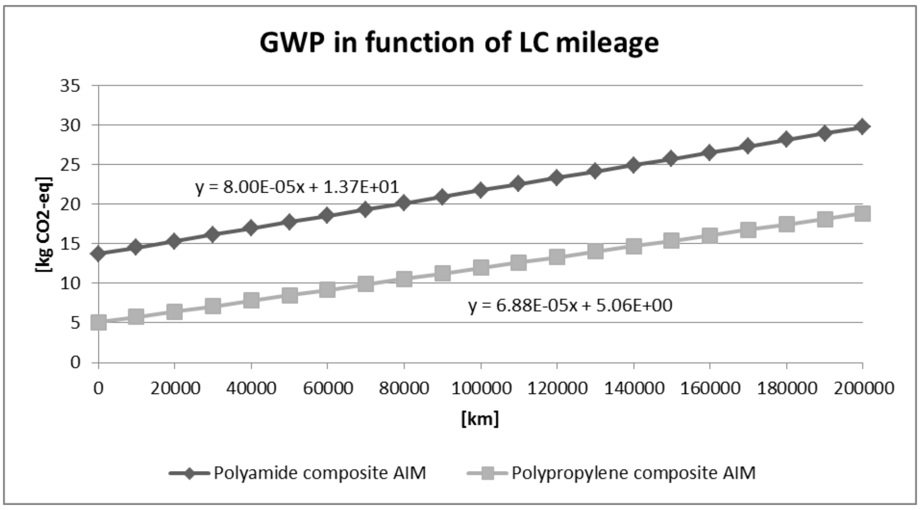

Figure 11 – Total GWP in function of LC mileage

A sensitivity analysis based on LCIA method has been performed: Figure 12 shows the percentage impacts of Polypropylene composite AIM with respect to Polyamide composite one taking into account the ILCD recommendation (Hiederer et al., 2011). Also in this case the Polypropylene composite AIM shows lower impacts.

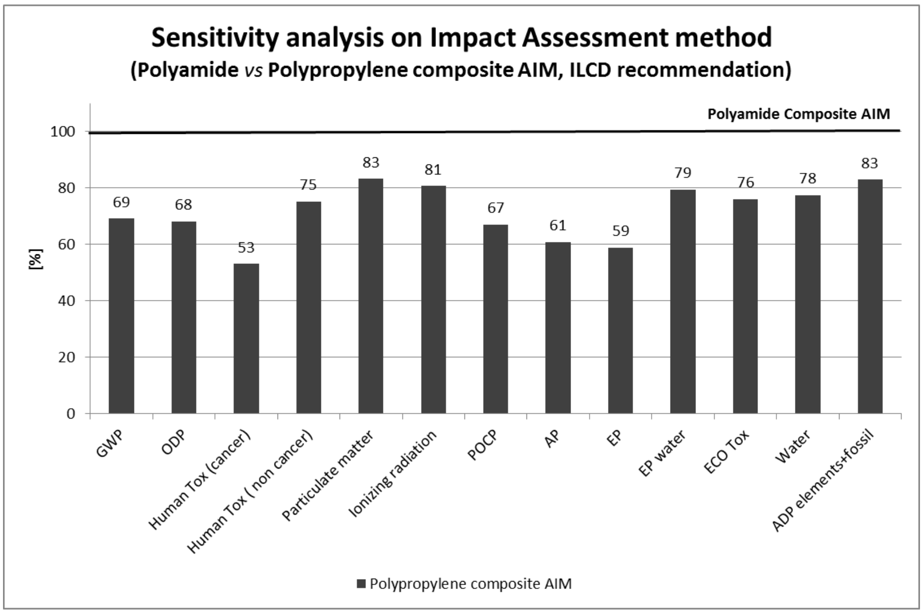

Figure 12 – Sensitivity analysis on LCIA method (Polyamide composite vs Polypropylene composite AIM, ILCD recommendation)

5. Conclusions

The intended application of the study is to provide support in the development of an AIM produced by Magneti Marelli®. The goal is to improve the knowledge on the potential impacts related to the involved materials and manufacturing processes.

In order to compare different AIM design solutions, a comparative LCA evaluating impacts on environment, resources consumptions and human health has been carried out. The entire AIM LC has been taken into account, including materials supply, production, 150000 km use, and end-of-life. The LCIA method CML 2001 has been chosen has it is scientifically valid and widely accepted.

The AIM case studies compared in the analysis differ for:

- the adoption of two alternative thermoplastic materials for the AIM production (Polyamide composite and Polypropylene composite);
- the introduction in the production stage of two new additional design solutions: Scraps recycling and Brass inserts elimination.

In comparison to existing studies, no LCAs on AIM made with Polypropylene are available; additionally this LCA examines a broader range of impacts, using primary data supplied by vehicle manufacturers whenever possible to reduce the uncertainty of the results.

LCIA results concerning the Polyamide composite AIM reveal that the most influential LC stages are use and materials supply: interventions of such stages amount to more than 90% for the majority of impact categories. This outcome is explicable by the considerable fuel consumption and emissions during the whole AIM life-time and the energy/resources consumption involved by PU "Raw materials extraction and production". Interventions of production stage do not exceed 13% for all the impact categories with the exception of ODP whose quota (22%) is totally attributable to PU "Manufacturing". EoL interventions are lower than 10% for all the impact categories.

The change of material from Polyamide composite to Polypropylene composite involves a considerable reduction of AIM LC impacts. Such outcome is confirmed by sensitivity analysis based on LCIA method in which the impacts have been evaluated taking into account the ILCD recommendation. For all the impact categories reductions are included in the range 27% - 50% with the exception of HTP for which the decrease is very high (94%) and ADP_e for which on the contrary the reduction is practically null. Considering contribution analysis by LC stage of impact, change of material evidences for the majority of impact categories a remarkable increase (10% - 20%) of use stage quota, totally to the detriment of materials supply intervention. The growth of use stage quota is explainable with the minor energy intensity of Polypropylene composite raw materials extraction and production despite the lower use stage impact involved by a lower AIM mass. Sensitivity analysis based on LC mileage (changes of ± 50000 km with respect to the reference LC mileage of 150000 km) confirms the advantages of Polypropylene composite AIM solution. Finally, no remarkable variations of Production and EoL contributions are involved by change of construction material.

The introduction in PU "Manufacturing" of scraps recycling entails negligible impact reduction for all the categories with respect to both Polyamide composite and Polypropylene composite AIM.

Brass inserts elimination leads to negligible impact reduction for all the categories with the exception of ADP_e for which saving is about 10% for both Polyamide composite and Polypropylene composite AIM.

Bibliography

Bates, P.., Mah, J.., Zou, X.., Wang, C.., Baylis, B., 2004. Vibration welding air intake manifolds from reinforced nylon 66, nylon 6 and polypropylene. Compos. Part Appl. Sci. Manuf. 35, 1107–1116. doi:10.1016/j.compositesa.2004.02.019

Battistoni, M., Pispola, G., Grimaldi, C.N., Mattogno, G., Bellato, N., 2006. Dependence of NVH Performance of Plastic Air Intake Manifolds on the Structural Design (SAE Technical Paper No. 2006-01-0705). SAE International, Warrendale, PA.

Bauhof, M.J., Castle, K.J., 1993. Design of an EGR Interface for Thermoplastic Intake Manifolds (SAE Technical Paper No. 930086). SAE International, Warrendale, PA.

Capitani, R., Pierini, M., Massimo, S., 1998. Definition and validation of a methodology industrially usable to analyse the dynamic behaviour of a car engine component made in plastic, in: Proceedings of the 23rd International Conference on Noise and Vibration Engineering, ISMA. pp. 639–646.

Capitani, R., Pierini, M., Massimo, S., 1999. Method for conducting validation testing on polyamide engine components, in: Proceedings of the International Modal Analysis Conference - IMAC. pp. 363–367.

Capitani, R., Pierini, M., Massimo, S., 2000. Method for conducting validation testing on polyamide engine components. Shock Vib. Dig. 32, 23.

Carlson, E., Nelson, K., 2003. Nylon Under the Hood: A History of Innovation.

Caskey, J., Daly, P., 1998. Effects of Rapid Strain Rates in Plastic Intake Manifolds (SAE Technical Paper No. 980729). SAE International, Warrendale, PA.

Defosse, M., 2009. Plastics in automotive design: Heavy emphasis on weight reduction. Mod. Plast. Worldw. 86, 92–93.

Dimeo, A., Alegre, G., Modeo, G., Bellato, N., Moura, T., 2012. Plastic Intake Manifold Influence on the NVH Performance in PFI Engine (SAE Technical Paper No. 2012-36-0615). SAE International, Warrendale, PA.

Edwards, K., Daly, P., 1999. Plastic Intake Manifolds - Geometric Growth for 7 Years (SAE Technical Paper No. 1999-01-0315). SAE International, Warrendale, PA.

Hickman, G.F., Schumacher, D., 2005. Polyamide Intake Manifold Shell Bonding (SAE Technical Paper No. 2005-01-1518). SAE International, Warrendale, PA.

Hiederer, R., European Commission., Joint Research Centre., Institute for Environment and Sustainability., 2011. International reference life cycle data system (ILCD) handbook: general guide for life cycle assessment: provisions and action steps. Publications Office, Luxembourg.

Hu, K., Lee, C., Homsi, E., Moenssen, D., 2003. Acoustic Modeling and Radiated Noise Prediction for Plastic Air-Intake Manifolds (SAE Technical Paper No. 2003-01-1448). SAE International, Warrendale, PA.

Kar, K., Keoleian, G.A., 1996. Application of Life Cycle Design to Aluminum Intake Manifolds (SAE Technical Paper No. 960410). SAE International, Warrendale, PA.

Keoleian, G.A., Kar, K., 1999. Life Cycle Design of Air Intake Manifolds: Phase I, 2.0 L Ford Contour Air Intake Manifold. Environmental Protection Agency, National Risk Management Research Laboratory.

Keoleian, G.A., Kar, K., 2003. Elucidating complex design and management tradeoffs through life cycle design: air intake manifold demonstration project. J. Clean. Prod. 11, 61–77. doi:10.1016/S0959-6526(02)00004-5

Klein, J., Wiese, J., 2011. High performance engineered polypropylene compounds for high temperature automotive under-the-hood applications. Presented at the Society of Plastics Engineers - 11th-Annual Automotive Composites Conference and Exhibition, ACCE 2011.

Koffler, Rodhe-Branderburger, 2010. On the calculation of fuel savings through lightweight design in automotive life cycle assessments. International Journal of Life Cycle Assessment (2010) 15:128-135. DOI 10.1007/s11367-009-0127-z.

Kondapalli, P.S., Sirani, V., 2000. General Guidelines for Improving Burst Pressure Strength of Welded Nylon Air Intake Manifolds (SAE Technical Paper No. 2000-01-0040). SAE International, Warrendale, PA.

Kraft, W.W., 2000. The Reduction of Air-Rush Noise in Plastic Engine Intake Manifolds (SAE Technical Paper No. 2000-01-0044). SAE International, Warrendale, PA.

Kraft, W.W., Sattler, E., Abboud, I., 1995. Noise Attenuation for Polyamide Intake Manifold (SAE Technical Paper No. 950232). SAE International, Warrendale, PA.

Lee, C.S., Kagan, V., Knowlden, N., Kim, K.W., Kim, H.-D., 1998. Optimization of Vibration Weld Joint Strength for Plastic Air Intake Manifold (SAE Technical Paper No. 980730). SAE International, Warrendale, PA.

LEE, K.-H., 1998. A Study on the Influence of Plastic Intake Manifold on the Performance and NVH of In-line 4 Cylinder Gasoline Engine (SAE Technical Paper No. 980728). SAE International, Warrendale, PA.

Mallick, P.K., Daly, P., 2000. Investigation of Thermoforming as a Method of Manufacturing Plastic Air Intake Manifolds (SAE Technical Paper No. 2000-01-0045). SAE International, Warrendale, PA.

Mathew, B.A., Wiebeck, H., 1999. Automotive Air Intake Manifold Application using Nylon 6,6 Composite Material (SAE Technical Paper No. 1999-01-3011). SAE International, Warrendale, PA.

Mukawa, T., Goto, Y., Sekine, N., Ikeda, Y., 1996. Development of a plastic intake manifold. JSAE Rev. 17, 51–57. doi:10.1016/0389-4304(95)00048-8

Nelson, K.W., 1995. Vibration Welding: A Low Cost Assembly Process for Thermoplastic Intake Manifolds (SAE Technical Paper No. 950230). SAE International, Warrendale, PA.
Novak, C., Gaspar, R., Fletcher, S., Daly, P., 2001. Development of a Plastic Manifold Noise Syntheses Technique (SAE Technical Paper No. 2001-01-1144). SAE International, Warrendale, PA.
Paffrath, H., Alex, M., Hummel, K.-E., 1999. Technology for Future Air Intake Systems (SAE Technical Paper No. 1999-01-0266). SAE International, Warrendale, PA.
Palmer, R.J., Norrey, C., Hayashi, R., Tres, D., 1996. Meeting Present and Future Global Materials Requirements for Nylon Air Intake Manifolds (SAE Technical Paper No. 960144). SAE International, Warrendale, PA.
PlasticsEurope, 2010. Plastics - the Facts 2010 - An analysis of European plastics production. demand and recovery for 2009.
Pricken, F., 1999. Top Acoustic of Plastic Air Intake Manifolds (SAE Technical Paper No. 1999-01-0319). SAE International, Warrendale, PA.
Schramm, J.G., 1992. Design Considerations for the Use of Composite Materials in Intake Manifolds and Fuel Rails (SAE Technical Paper No. 922149). SAE International, Warrendale, PA.
Schuckert, M., Dekorsy, T., Pfleiderer, I., Eyerer, P., 1993. Developing a Comprehensive Balance of an Automobile Air Intake Manifold. Kunststoffe - Ger. Plast. 83, 16–19.
Siavoshani, S., Stickler, M., Nehme, H., Krajewski, B., 2001. Analytical and Experimental Techniques in Solving the Plastic Intake Manifold NVH (SAE Technical Paper No. 2001-01-1544). SAE International, Warrendale, PA.
Sievewright, G., 2000. Air Flow Noise of Plastic Air Intake Manifolds (SAE Technical Paper No. 2000-01-0028). SAE International, Warrendale, PA.
Sievewright, G.P., 1998. Noise Optimisation of Plastic Air Intake Manifolds (SAE Technical Paper No. 980273). SAE International, Warrendale, PA.
Spitzley, D.V., Keoleian, G.A., 2001. Life Cycle Design of Air Intake Manifolds, Phase II: Lower Plenum of the 5.4 L F-250 Air Intake Manifold, Including Recycling Scenarios. Ann Arbor 1001, 48109–1115.
Tanaka, H., Kitagawa, S., 2007. Development of a Plastic Intake Manifold with CAE (SAE Technical Paper No. 2007-01-3549). SAE International, Warrendale, PA.
Thatcher, R., Storr, P., Green, P., 1992. Plastic intake manifold. Mater. Des. 13, 353–358. doi:10.1016/0261-3069(92)90006-4
Todd, F., Pascoe, G., 1987. The Production of Hollow Plastics Components (SAE Technical Paper No. 870539). SAE International, Warrendale, PA.
University of Leiden, 2001. Centre for Environmental Studies (CML) [WWW Document]. URL http://www.cml.leiden.edu/ (accessed 1.28.14).
Villalva, S., Alegre, G., Moura, T., Windlin, F., Savioli, A., Motta, P., 2012. Air Intake Manifolds Manufactured with Chemically Recycled Material Achieve a Reduction of CO2 Emissions and Costs Saving with Similar Mechanical Resistance (SAE Technical Paper No. 2012-36-0368). SAE International, Warrendale, PA.
Wehr, D., Huurdeman, B., Spennemann, A., 2002. EGR - A Challenge for Modern Plastic Intake Manifolds (SAE Technical Paper No. 2002-01-0902). SAE International, Warrendale, PA.
Yamaguchi, S., 2000. Development of Plastic Intake Manifold by DRI Process (SAE Technical Paper No. 2000-01-0041). SAE International, Warrendale, PA.
Zucchelli, A., Curioni, S., Lanzellotto, T., Minak, G., 2009. Bursting Tests of a Short Fiber Reinforced Composite Air Intake Manifold. Presented at the ICCM-17 17th International Conference on Composite Materials, Edinburgh, UK.

Tables:

Component	Material	Q.ty	Mass [kg]	Mass [kg/AIM]
Central Body	PA6GF30	1	1.024	1.024
Lower Cover	PA6GF30	1	0.316	0.316
Upper Cover	PA6GF30	1	0.440	0.440
Throttle Body Gasket	P-CuZn40Pb 2	4	0.0024	0.0096
Runner Gasket	CuZn38Pb 1.5	1	0.0061	0.0061
Throttle Body Brass Inserts	FKM	4	0.0022	0.0088
Filter Insert	FKM	1	0.0046	0.0046
Compression Limiters	CF9SMnPb36 - Fe//Zn8//C	6	0.0101	0.0606

Table A - LCI data for PU “Raw materials extraction and production”

Component	Material	Q.ty	Mass [kg]	Mass [kg/AIM]
PP Central Body	PPGF35	1	0.870	0.870
PP Lower Cover	PPGF35	1	0.269	0.269
PP Upper Cover	PPGF35	1	0.374	0.374

Table B – Mass of plastic components in the Polypropylene AIM case studies

Identification	Description
Case study 1 (Reference)	Polyamide composite AIM
Case study 2	Polyamide composite AIM & Scraps recycling
Case study 3	Polyamide composite AIM & Brass inserts elimination
Case study 4	Polypropylene composite AIM
Case study 5	Polypropylene composite AIM & Scraps recycling
Case study 6	Polypropylene composite AIM & Brass inserts elimination

Table C – Description of AIM alternative case studies

	Stage	Process Unit (PU)	Process
AIM Life Cycle	Materials supply	Raw materials extraction and production	Production of electricity, heat, steam and fuel for raw materials extraction and production
			Raw materials extraction and production processes
		Raw materials transportations	Fuel production for raw materials transportations to MM plants
	Production	Manufacturing	Production of electricity, heat, steam, fuel and auxiliary material for manufacturing processes performed inside MM plants: - Raw material distribution; - Re-milling; - Drying; - Moulding; - Welding; - Brass insert assembly; - Compression limiter assembly; - Gaskets assembly; - Leakage test; - Packaging

			Manufacturing processes
		Internal transportations	Fuel production for AIM internal transportations between MM plants
	Use	-	Production of fuel consumed by the car attributable to AIM
	EoL	-	Production of electricity, heat, steam and fuel for materials disassembly, shredding and recycling
			Landfilling of waste materials

Table D - Schematization of AIM LC: subdivision in stages, PUs and single processes

Component	**Travelled distance (Supplier - MM) [km]**	**Highway [%]**	**Rural [%]**	**Truck payload [t]**
AIM raw material (Polyamide composite)	240	74	26	23 (Truck trailer)
Filter and throttle body inserts	1230	96	4	1 (Van)
Throttle body and runner gaskets	193	80	20	2.1 (Truck)
Compression limiter	273	87	13	5 (Truck)

Table E - Data collected for PU "Raw materials transportation"

Component	**Travelled distance (MM – Customer) [km]**	**Highway [%]**	**Rural [%]**	**Truck typology [t]**
AIM	506	94	6	24 (Truck trailer)

Table F - Data collected for PU "Internal transportations"

Gasoline	
Vehicle model	1600 cm^3, 74 kW
Vehicle mass [kg]	1280
Emission stage	EURO 5
Vehicle fuel consumption (mixed urban-extra) [l/100km]	6.4
CO_2 emissions [g/km]	164
SO_2 emissions [kg/km]	1.05E-06
Use stage [km]	150000

Table G - Technical data referring to car model equipped by AIM FIRE

Excluded AIM LC processes	**Motivation of exclusion**
Brass inserts production	No information from the supplier (Brass inserts mass = 0.5% of total AIM mass)
Compression limiters production	No information from the supplier (Compression limiters mass = 3.2% of total AIM mass)

Gaskets FKM rubber production	Only energy consumption data from the supplier (Gaskets mass = 0.8% of total AIM mass)

Table H - AIM LC processes excluded from the LCA

Manufacturing – Production Data collection	Source	Notes/Assumptions	Reference year	Geographical zone
Injection moulding	Magneti Marelli	LCI data on material and energy consumption measured in MM Crevalcore plant; time measure ~ 1h and ~n°60 pieces/h	2012	IT
Vacuum system				
Dry system				
Welding				
Brass inserts assembly	Magneti Marelli	LCI data on material and energy consumption measured in MM Crevalcore plant; time measure ~ 1h, ~n°60 pieces/h	2012	IT
Compression limiter assembly				
Gaskets assembly + leakage test				

Table I – Primary data (Magneti Marelli production processes)

Material/ Energy Production/ Transportation	Database name	Source	Notes/Assumptions	Reference year	Validity time	Geographical zone
Polyamide	Gabi 6 database	PE	-	2011	2014	IT
Polypropylene	Gabi 6 database	PE	-	2011	2014	DE
Glass fiber	Gabi 6 database	PE	-	2011	2014	DE
Electricity grid mix	Gabi 6 database	PE	-	2009	2014	IT
Lube oil	Gabi 6 database	PE	-	2009	2014	IT
Brass (P-CuZn40Pb2, CuZn38Pb1.5)	Gabi 6 database	PE	Replaced by GaBi CuZn39Pb3 alloy (the total mass of the brass inserts is about 0.5% of the total AIM mass)	2011	2014	RER
Steel CF9SMnPb36 Riv.Fe//Zn8//C	Gabi 6 database	PE	Replaced with Steel cast part alloyed (the total mass of the compression limiters is about 3.2% of the total AIM mass)	2011	2014	DE
FKM rubber	Gabi 6 database	PE	Replaced with NBR rubber production (the total mass of the gaskets is about 0.8% of the total AIM mass)	2011	2014	DE
Gaskets FKM rubber production	-	-	Only energy consumption data available from the Supplier	-	-	IT
Truck Euro 0-5 mix Up to 7,5 t gross weight	Gabi 6 database	PE	Customized parameters: • Distance	2011	2014	GLO

Truck-trailer Euro 0-5 mix 34-40 t gross weight			• Payload • Share motorway • Share urban • Share rural • Utilization			
Diesel mix	GaBi 6 database	PE	-	2009	2014	EU-27

Table J – Secondary data

Polyamide composite AIM (reference)

	MATERIALS SUPPLY	PRODUCTION		USE	EoL	Total LC
		Manufacturing	Internal transportations			
Abiotic Depletion Potential (ADP elements) [kg Sb-eq.]	1.03E-04	1.49E-07	8.29E-09	3.53E-07	3.11E-08	1.03E-04
Abiotic Depletion Potential (ADP fossil)	2.15E+02	1.43E+01	3.08E+00	1.59E+02	2.56E+00	3.94E+02
Acidification Potential (AP) [kg SO2-eq.]	3.81E-02	2.67E-03	1.08E-03	1.42E-02	4.98E-04	5.65E-02
Eutrophication Potential (EP) [kg Phosphate-eq.]	3.38E-03	1.79E-04	2.51E-04	1.23E-03	4.82E-04	5.52E-03
Freshwater Aquatic EcoTox Pot. (FAETP) [kg DCB-eq.]	1.72E-02	1.57E-03	5.24E-04	1.44E-02	6.15E-04	3.42E-02
Global Warming Potential (GWP) [kg CO_2 - eq]	1.24E+01	9.95E-01	2.22E-01	1.20E+01	1.71E-01	2.57E+01
Human Toxicity Potential (HTP) [kg DCB-eq.]	5.09E+00	3.41E-02	5.98E-03	2.15E-01	5.41E-03	5.35E+00
Marine Aquatic EcoTox Pot. (MAETP) [kg DCB-eq.]	2.48E+02	5.44E+01	1.65E+00	9.62E+01	1.48E+01	4.15E+02
Ozone Layer Depletion Potential (ODP) [kg R11-eq.]	1.05E-09	3.88E-10	3.89E-12	2.03E-10	8.28E-11	1.73E-09
Phot. Ozone Creation Pot. (POCP) [kg Ethene-Eq.]	2.40E+02	1.87E+01	3.43E+00	1.77E+02	3.01E+00	4.42E+02
Primary Energy Demand (PED) [MJ]	9.13E-03	2.10E-04	-3.94E-04	2.03E-03	6.84E-05	1.10E-02
Terrestric Ecotoxicity Potential (TETP inf.)	1.70E-02	2.80E-03	1.64E-03	1.76E-02	3.27E-03	4.23E-02

Table K - LCIA results for Polyamide composite AIM (reference)

Polypropylene composite AIM

	MATERIALS SUPPLY	PRODUCTION		USE	EoL	Total LC
		Manufacturing	Internal transportations			
Abiotic Depletion Potential (ADP elements) [kg Sb-eq.]	1.00E-04	1.12E-07	7.14E-09	3.04E-07	2.67E-08	1.01E-04
Abiotic Depletion Potential (ADP fossil)	9.55E+01	1.07E+01	2.65E+00	1.37E+02	2.20E+00	2.48E+02
Acidification Potential (AP) [kg SO2-eq.]	1.44E-02	2.00E-03	9.28E-04	1.22E-02	4.28E-04	2.99E-02
Eutrophication Potential (EP) [kg Phosphate-eq.]	1.50E-03	1.34E-04	2.16E-04	1.06E-03	4.14E-04	3.32E-03
Freshwater Aquatic EcoTox Pot. (FAETP) [kg DCB-eq.]	1.00E-02	1.19E-03	4.51E-04	1.24E-02	5.29E-04	2.46E-02
Global Warming Potential (GWP) [kg CO_2 - eq]	3.97E+00	7.45E-01	1.92E-01	1.03E+01	1.47E-01	1.54E+01
Human Toxicity Potential (HTP) [kg DCB-eq.]	1.03E-01	2.55E-02	5.15E-03	1.85E-01	4.65E-03	3.23E-01
Marine Aquatic EcoTox Pot. (MAETP) [kg DCB-eq.]	1.66E+02	4.07E+01	1.42E+00	8.28E+01	1.27E+01	3.04E+02
Ozone Layer Depletion Potential (ODP) [kg R11-eq.]	7.08E-10	2.91E-10	3.35E-12	1.74E-10	7.13E-11	1.25E-09
Phot. Ozone Creation Pot. (POCP) [kg Ethene-Eq.]	1.07E+02	1.40E+01	2.95E+00	1.53E+02	2.59E+00	2.79E+02
Primary Energy Demand (PED) [MJ]	3.91E-03	1.57E-04	-3.39E-04	1.75E-03	5.89E-05	5.53E-03
Terrestric Ecotoxicity Potential (TETP inf.)	7.71E-03	2.10E-03	1.41E-03	1.52E-02	2.82E-03	2.92E-02

Table L - LCIA results for Polypropylene composite AIM

Figures:

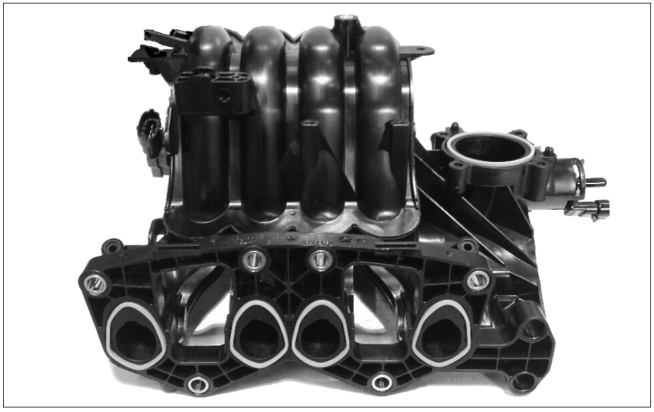

Figure A – Image of the complete AIM

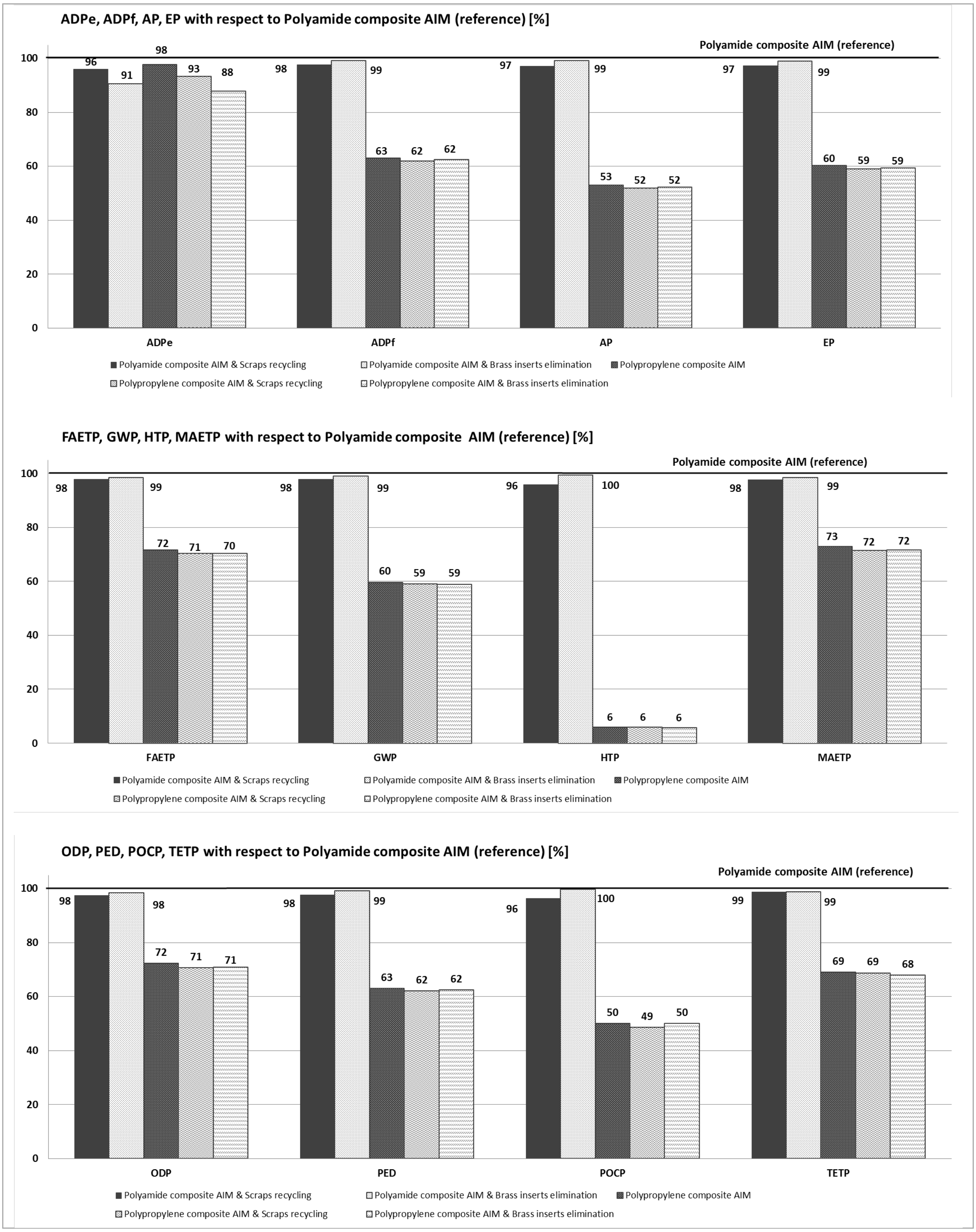

Figure 1 - Complete set of LCIA results of all cases; data are expressed as % of impact of Polyamide composite AIM (reference)

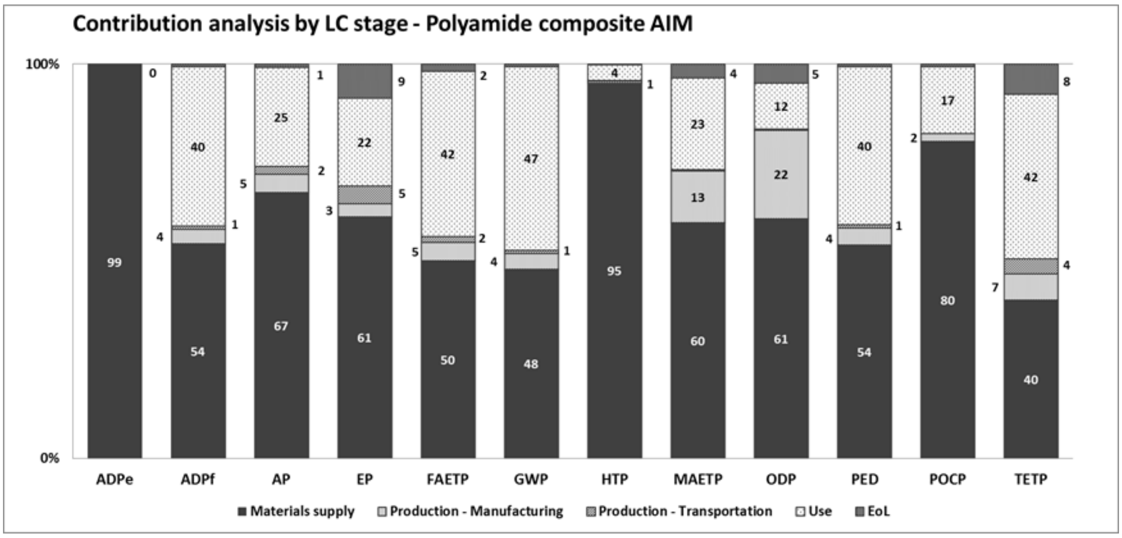

Figure 2 - Contribution analysis by LC stage for Polyamide composite AIM (reference)

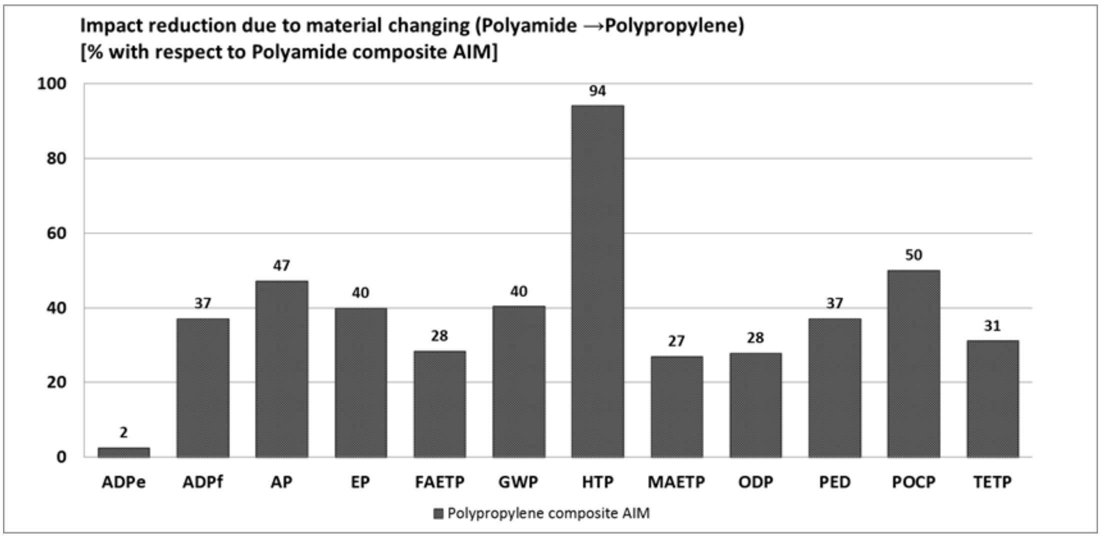

Figure 3 - LCIA results for Polypropylene composite AIM expressed as % of Polyamide composite AIM (reference)

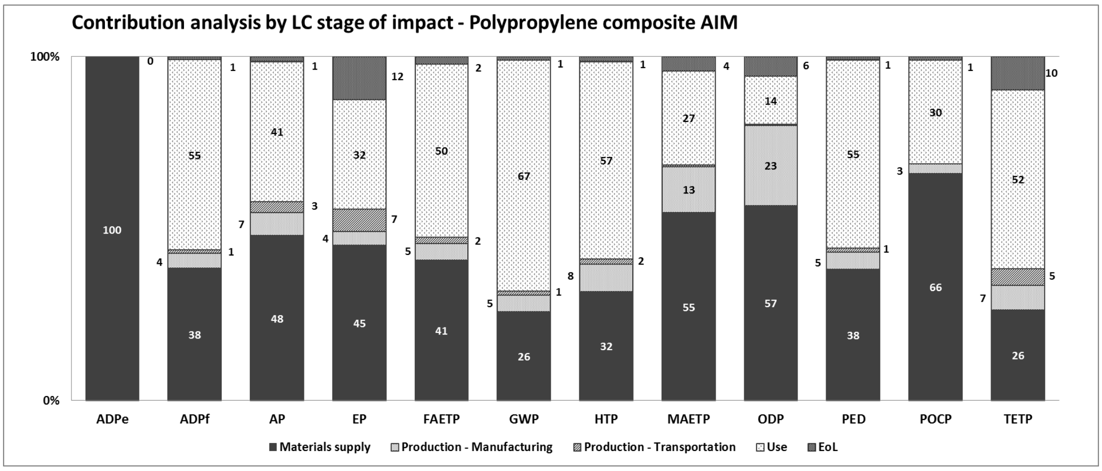

Figure 4 - Contribution analysis by LC stage for Polypropylene composite AIM

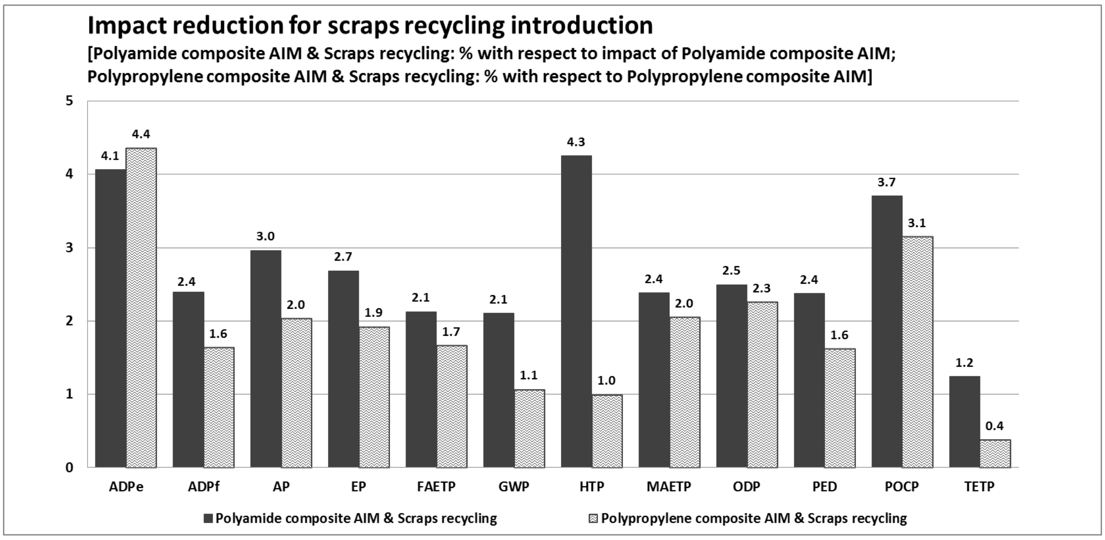

Figure 5 - Impact reduction for introduction of scraps recycling [Polyamide composite & scraps recycling : % with respect to impact of Polyamide composite AIM; Polypropylene composite AIM & scraps recycling: % with respect to impact of Polypropylene composite AIM]

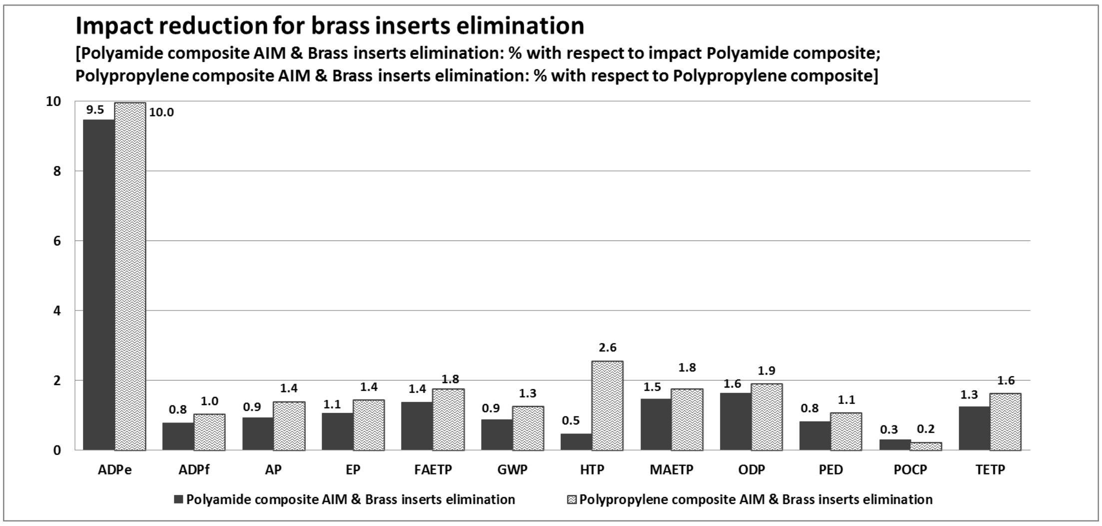

Figure 6 - Impact reduction for brass inserts elimination [Polyamide composite AIM & brass inserts elimination: % with respect to impact of Polyamide composite AIM; Polypropylene composite AIM & brass inserts elimination: % with respect to Polypropylene composite]

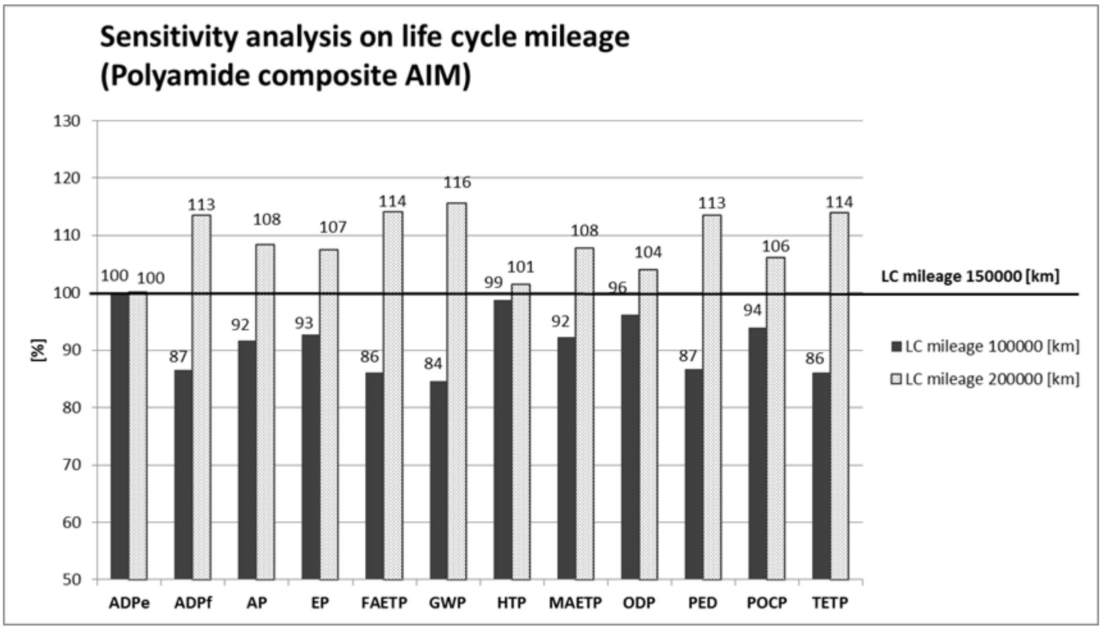

Figure 7 – Sensitivity analysis on LC mileage (Polyamide composite AIM)

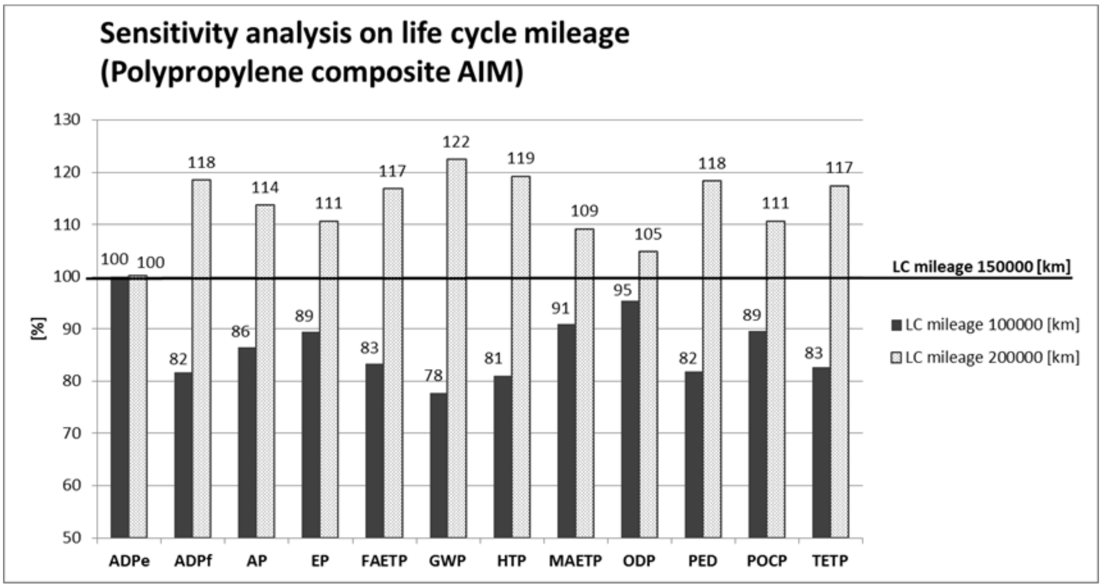

Figure 8 - Sensitivity analysis on LC mileage (Polypropylene composite AIM)

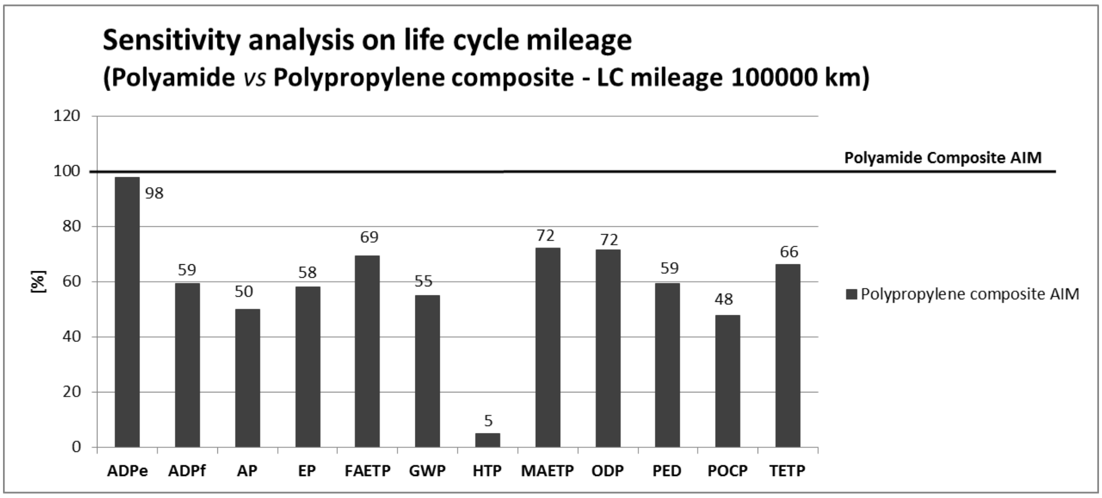

Figure 9 - Sensitivity analysis on LC mileage (Polyamide vs Polypropylene composite AIM, LC mileage 100000 km)

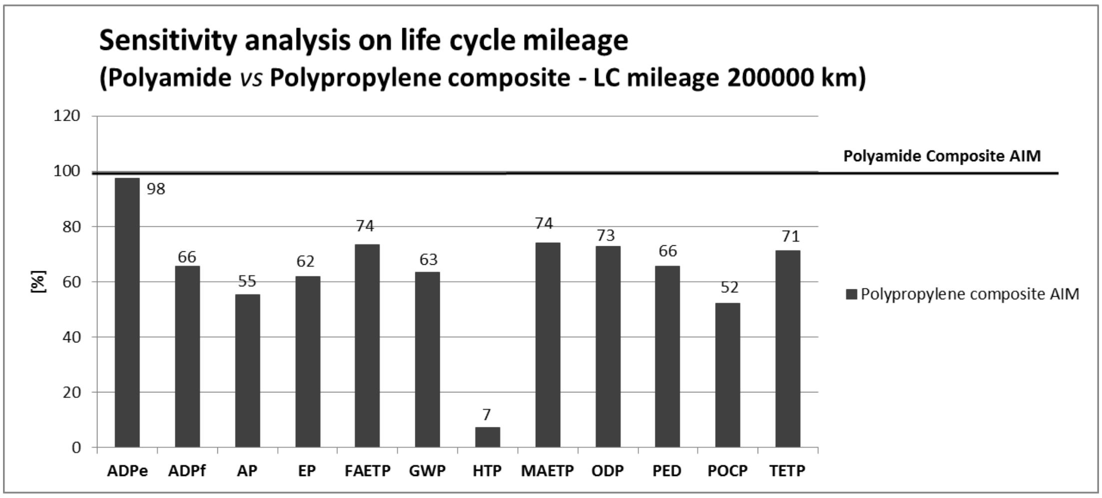

Figure 10 - Sensitivity analysis on LC mileage (Polyamide vs Polypropylene composite AIM, LC mileage 200000 km)

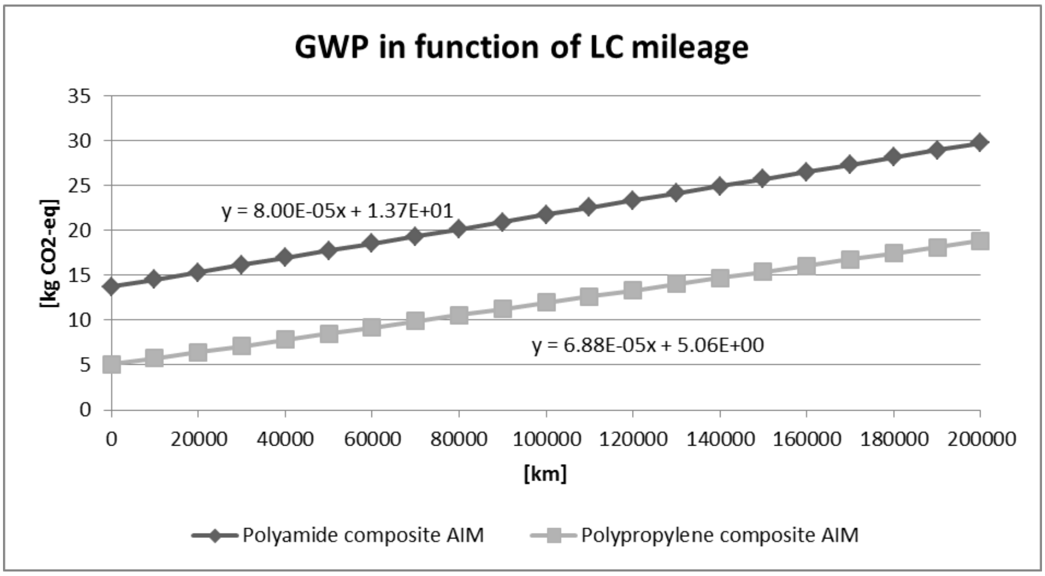

Figure 11 – Total GWP in function of LC mileage

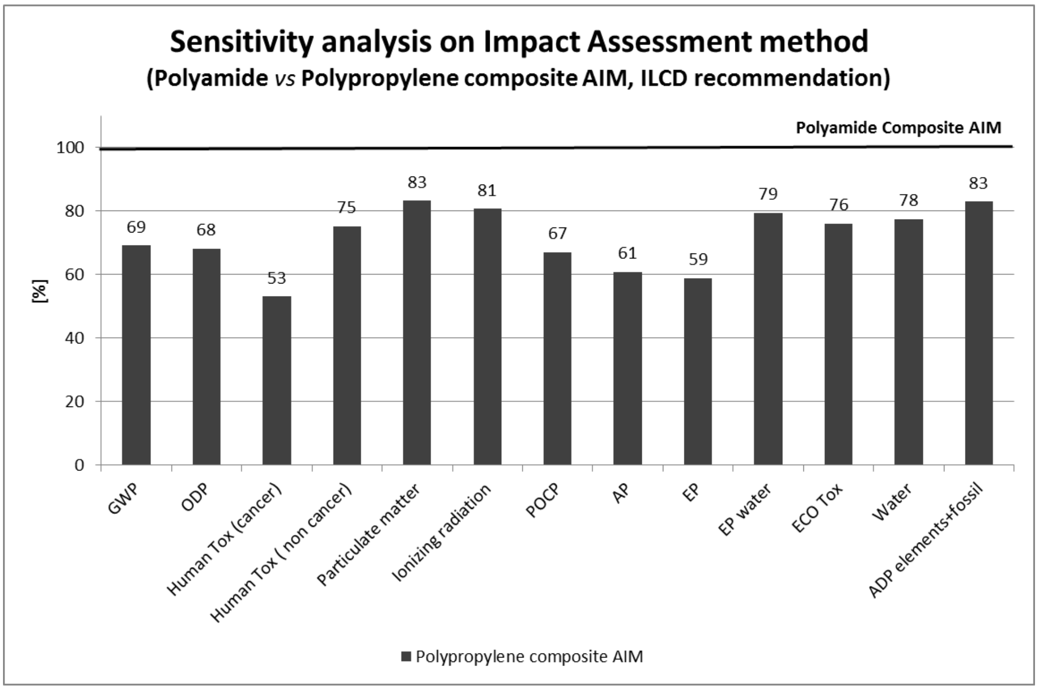

Figure 12 – Sensitivity analysis on LCIA method (Polyamide composite vs Polypropylene composite, ILCD recommendation)