The International Journal of Life Cycle Assessment (2018) 23:2043–2054
https://doi.org/10.1007/s11367-017-1433-5

MODERN INDIVIDUAL MOBILITY

Lightweighting in light commercial vehicles: cradle-to-grave life cycle assessment of a safety-relevant component

Silvia Cecchel[1] · Daniel Chindamo[1] · Massimo Collotta[1] · Giovanna Cornacchia[1] · Andrea Panvini[1] · Giuseppe Tomasoni[1] · Marco Gadola[1]

Received: 14 December 2016 / Accepted: 20 December 2017 / Published online: 5 January 2018

Abstract

Purpose Currently, the reduction of weight in automotive is a very important topic in order to lower the air pollution. In this context, the purpose of the present paper was to analyze a real case study through a comparison of the environmental sustainability between a conventional steel crossbeam for light commercial vehicles and an innovative lightweight aluminum one.

Methods For both scenarios, a cradle-to-grave life cycle assessment methodology and a sensitivity analysis has been used through the study of the following phases: mineral extraction, component manufacturing, use on vehicle, and end of life. In particular, many primary data and a complete vehicle model simulation with three different European driving cycles have been used in order to reach the highest possible level of accuracy during the analysis.

Results and discussion Regarding the manufacturing phase, the aluminum component's production gave the highest impact because of the high energy required in the mineral reduction. Anyway, this stage of the analysis had a low effect on the entire LCA, because the benefit of weight reduction during vehicle use showed a strongly higher contribution. The urban driving cycle had the most relevant impact, as a consequence of the frequent start and stop operations and the longest time with engine at idle speed, while the extra-urban cycle is the less demanding due to its higher average speed and no start and stop.

Conclusions In conclusion, the present research demonstrated the environmental importance of the lightweight for an actual case study in the commercial vehicles field.

Keywords Aluminum · Automotive · Commercial vehicles · Life cycle assessment (LCA) · Lightweighting · Steel

1 Introduction

The reduction of pollution in transport is a matter of increasing relevance, in the perspective of an improved world sustainability. For this purpose, the present EU legislation imposes restrictive targets of emissions' reduction for new vehicles by 2020, with a CO_2 limit for passenger cars and for light commercial vehicles (LCVs), respectively of 95 and 147 g/km (Commission 2012). In this context, the lightweighting is an important measure for improving traffic emission reductions. Different researchers have estimated future scenarios for the reduction of vehicle weight (McKinsey and Company, 2012; Martino 2017; Cheah 2010; Weccard 2012). These studies evaluated a lightweighting that varied from 15% for medium/small vehicles to 35% for luxury cars. For commercial vehicles, the future trend is assumed to be of 20% weight reduction (Cecchel et al. 2018). In particular, fuel savings are estimated to be 0.3–0.5 l/(100 × 100 kg) for gasoline passengers car and 0.29–0.33 l/(100 × 100 kg) for diesel passenger cars with adjustments in the rear axle transmissions to the new power to weight ratio, while for articulated trucks, the fuel savings are estimated to be 0.03 l/(100 × 100 kg) on flat highway and up to 0.1 l/(100 × 100 kg) in urban traffic situations, due to frequent accelerations. Average fuel savings turn out to be about 0.06 l per 100 km for a 100-kg weight reduction (Helms and Lambrecht 2007), and the potential saving of greenhouse gas emissions related to a persistent lightweighting of passenger cars between 2010 and 2050 are estimated to be about 9–18 gigatons $CO_{2\text{-eq}}$ compared to the current level (Modaresi et al. 2014).

Responsible editor: Wulf-Peter Schmidt

✉ Silvia Cecchel
s.cecchel@unibs.it

[1] DIMI, Department of Industrial and Mechanical Engineering, University of Brescia, via Branze 38, 25123 Brescia, Italy

The above considerations clarify the reason why the replacement of conventional alloys (i.e., steel and cast iron) with low-density materials (i.e., aluminum alloys) quickly increased during the last few years (Kasai 1999; Hirsch 2004; Cecchel and Ferrario 2016). This approach is usually connected with a design optimization and with the use of advanced manufacturing technologies, which can provide valuable weight reduction together with the preservation of the safety and performance levels required by automotive standards (Das et al. 2016).

In particular, high-pressure die casting (HPDC) of aluminum alloys is one of the most employed technologies for high volume production of lightweight components.

This process is characterized by high productivity rates and near net shape components production, features which ensure a reduction of weight between 30 and 50% in comparison with conventional steel components (Gunasegaram and Tharumarajah 2009). Anyway, lightweight is not widely applied yet in the same way across all vehicle segments due to cost limitations, specific material resistance, and stiffness requirements. Indeed, the use of heavy metals is still predominant for commercial vehicles and busses, especially for safety-relevant parts, and the lightening of this important class of components is a very recent topic (Cecchel and Ferrario 2016). It is worthwhile to note that, apart from emission reductions during vehicle use, the adoption of lighter components may result in environmental side effects that should be taken into account as well. Complete works on the effectiveness of weight reduction for the category of components analyzed in this work (safety-relevant products for commercial vehicles) are not so many, even if some studies have been published on the general analysis of automotive lightweighting. In detail, these researches are almost all based on life cycle assessment methodology and confirmed the environmental advantages given by iron and steel substitution with lighter materials (Kim and Wallington 2013).Some of these studies focus on the entire automotive sector, discussing the benefits of vehicles lightweighting in different countries (Puri et al. 2009; Kim et al. 2010a; Kim et al. 2011; Keoleian and Sullivan 2012), while other research works focus mainly on the use of different lightening materials and technologies (i.e., aluminum alloys; Bertram et al. 2009; Das 2014), high-strength steel (Kim et al. 2010b), magnesium alloys (Hakamada et al. 2007; Du et al. 2010), natural fibers (Boland et al. 2015), various materials (Kelly et al. 2015; Raugei et al. 2015). In this context, it is important to highlight that very few works which investigate in detail the foundry production step by step have been found (Dalquist and Gutowski 2006; Gunasegaram and Tharumarajah 2009; Singh 2013). The present work is based on this last approach as well as on some of the authors' previous research (Cecchel et al. 2016).

On the calculation of fuel savings through vehicle lightweighting, in order to achieve a better fuel consumption estimation, a complete vehicle model has been used instead of the usual fuel reduction value (FRV) approach found in literature (Wötzel et al. 1999; Wohlecker et al. 2007; Ribeiro et al. 2007). The FRV approach basically presents the fuel consumption rate as a linear function of vehicle mass (Keoleian and Sullivan 2012; Kim and Wallington 2013). On the other hand, the model used for this study is a consolidated tool and its results in terms of fuel consumption prediction are very accurate as it takes into account, among others, tire rolling resistance, powertrain spin inertias, and aerodynamic resistance effects (Chindamo et al. 2014b).

Calculations have been made on three different driving scenarios; they are the European city/urban driving cycle (ECE-12), the Extra-Urban Driving Cycle (EUDC), and the New European Driving Cycle (NEDC). Such driving cycles represent the typical driving condition in Europe and they have been previously used in similar works (Koffler and Rohde-Brandenburger 2009; Baptista et al. 2011).

In order to comprehensively evaluate the environmental benefits over the entire life cycle of lightened vehicles or components, different impact categories are reported in life cycle assessment (LCA) literature studies. In particular, several papers highlight the importance of the reduction of the greenhouse gas (GHG) parameter for the analysis of the climate change (Maclean and Lave 2003; Duflou et al. 2009). Moreover, the lightening of automotive components also affects other impact categories often referred to the transportation sector, for example, human toxicity and fossil depletion. With reference to the human toxicity, this impact mainly depends on energy demand and, in particular, air emissions deriving from coal and oil combustion. The impact on fossil depletion and human health is also related to energy demand. In conclusion, all of these factors needs to be taken into account in order to support the decision not just from an environmental but also from an economic and social point of view (Dalquist and Gutowski 2006; Singh 2013). During the present research, these features were investigated through the use of a cradle to grave life cycle assessment methodology and a sensitivity analysis.

In particular, the aim of this work was to evaluate comprehensively the environmental benefits over the entire life cycle of weight-reduced components. For this purpose, a real case study was analyzed through a comparison of the environmental sustainability between an innovative lightweight high-pressure die casting primary aluminum suspension crossbeam (PASC) for light commercial vehicles and a conventional steel sheets suspension crossbeam (SSC) one. In detail, SSC weighs 30 kg and PASC weighs 15 kg, thanks to a remarkable lightweighting achieved after a proper research and development of a new design. A cradle-to-grave life cycle assessment methodology and a sensitivity analysis were used through the analysis of the following phases: mineral extraction, component manufacturing, use on vehicle, and end of life. Important items were the use of many primary data and the integration of a complete vehicle model simulation with three different European driving cycles in order to reach the highest possible level of accuracy during the analysis.

2 Materials and methods

2.1 Life cycle assessment

According to ISO 14040 (though this study is not fully compliant to this standard), LCA is a methodology used to assess the environmental impacts associated with all stages of a product's life, from cradle to grave (International Standards Organization 2007). It involves different stages of analysis that are outlined below.

2.2 Goal and scope definition

The aim of this LCA analysis is to analyze the potential environmental benefits arising from the employment of a commercial vehicle with an innovative lightweight aluminum high-pressure die casting (HPDC) crossbeam suspension (PASC, scenario 1) in replacement of the conventional heavier steel component (SSC, scenario 2). Indeed, the use of a lighter component implies a well-known emission reduction, but its energy-intensive production needs to be properly considered in order to establish which one of these aspects prevail. In detail, important features are the high amount of energy required both by the electrolysis in the primary aluminum ingot production and by the foundry process.

The functional unit adopted for both scenarios analyzed was a life-time mileage of 350,000 km for a single component assembled on a commercial vehicle. The component weight is 15 kg for scenario 1 and 30 kg for scenario 2, thanks to the innovative lightweighting achieved by means of a proper material selection as well as a careful design, supported by an advanced engineering approach explained in detail in a previous work (Cecchel and Ferrario 2016).

For each scenario, the boundaries of the life cycle considered in the analysis include all the phases from mineral extraction to recycling and landfilling process, while environmental factors and uncertainties related to construction of the facilities for foundries and finishing are neglected as they were not deemed significant.

Flows presented in Figs. 1 and 2 show a schematic summary of the mass and energy input/output respectively for the scenario 1 (PASC) and scenario 2 (SSC). Indeed, the phases analyzed comprise all the processes explained in the "Material and method" section, from the raw material extraction until the use of the component on a light commercial vehicle.

2.3 Life cycle inventory

During the life cycle inventory phase, the relevant mass and energy input and output flows to be included in the analysis are identified and measured.

Some relevant details about the component's production stage and its entire life cycle are reported for each scenario in this section.

With reference to scenario 1, the first life cycle stage for aluminum component production consists in the extraction of the ore and its transformation into a primary aluminum ingot, through the following operations: bauxite mining, alumina production, electrolysis, and cast housing.

In particular, bauxite is the standard raw material for aluminum production and has to be processed into alumina through the use of the Bayer chemical process that takes place in autoclaves with caustic soda and lime. Then, the aluminum hydroxide is calcined in order to obtain the end-product. Currently, about 2250 kg of bauxite are required for producing 1000 kg of alumina (Buxmann et al. 2006; European Aluminum Association 2013). After that, pure alumina is reduced into primary aluminum by means of the electrolysis Hall-Héroult process. The reduction of alumina into liquid aluminum is operated under high-intensity electrical current. The electrical energy required for the primary smelting

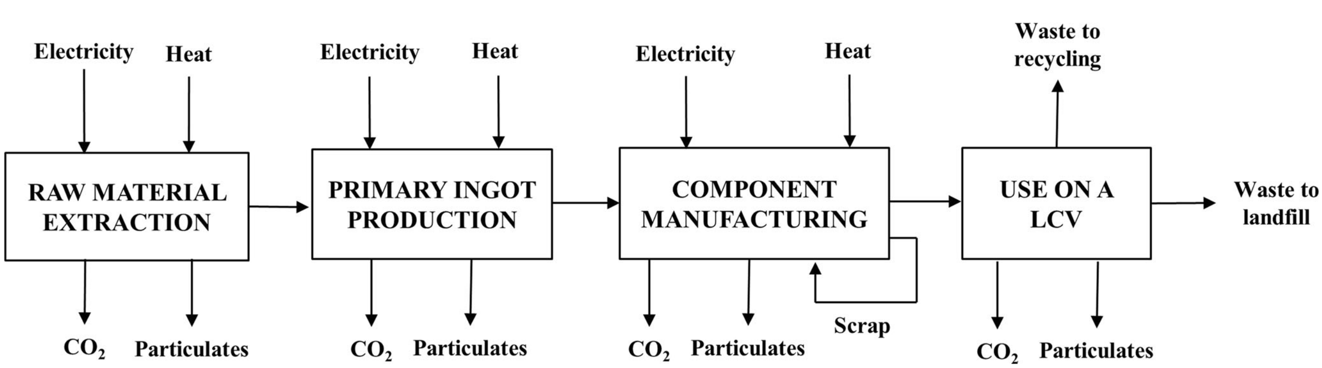

Fig. 1 Input/output flows of scenario 1 (primary aluminum suspension crossbeam)

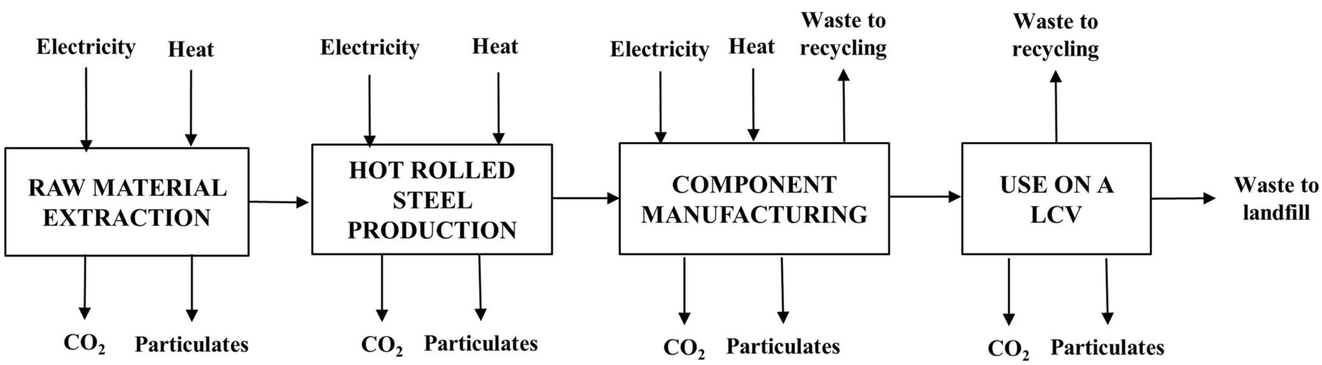

Fig. 2 Input/output flows of scenario 2 (steel suspension crossbeam)

process constitutes the major part of energy consumption in primary aluminum production and is one of the main important phases for the production stage of the LCA (Buxmann et al. 2006; European Aluminum Association 2013). Furthermore, about 1920 kg of alumina is required to produce 1000 kg of aluminum. Finally, molten aluminum is alloyed and casted into a primary aluminum ingot.

After that, the component is manufactured through the process of HPDC composed by the following phases: aluminum ingot melting, molten metal holding, and casting. In detail, ingots are melted into a furnace, and subsequently, the liquid alloy is transferred into another one in order to maintain the temperature (Dalquist and Gutowski 2004). Thereafter, the molten material is fed from the holding furnace into the HPDC machine and then injected at high pressure into a steel mold to obtain the required shape of the products.

Subsequently, the alloy solidifies into the die cavity, including not only the actual part (formed in the cavity) but also the feeding system and the overflows that has to be trimmed off and directly recycled in-house by remelting (Parashar and Mittal 2004; Bakemeyer 2008).

Then, the castings are subjected to machining in order to obtain the final design required by the component features. Thanks to the typical aluminum corrosion resistance, no protective treatment is required for this new version of suspension crossbeam.

With reference to scenario 2, the first life cycle stage for steel component production consists in the extraction of the iron ore and its transformation into a hot rolled sheet coil, with the following operations: iron ore mining, molten iron production, transformation into liquid steel, casting of a thin slab, which is finally rolled into a coil with the thickness required.

In detail, iron ore is usually reduced into molten iron in a blast furnace, where it is introduced with oxygen, natural gas, coal, coke, and limestone. Then, molten iron is transferred into an electric arc furnace with recycled steel scrap, lime, oxygen, and alloying elements, giving as output liquid steel with the required chemical composition. Afterwards, steel is directly cast as a thin slab that is subsequently fed to the finishing mill to obtain the final thickness of the coil.

After that, the hot rolled coil is trimmed into the various steel sheet metals with the specific shape required, which are then folded and welded together. The raw component is then machined to the final shape, and finally, it is painted to prevent corrosion.

Finally, crossbeams are assembled on vehicles and perform their function until they are recycled or disposed at the end of life. In particular, the material collected is recovered after disassembling, shredding, separating, and sorting.

It is worthwhile to note that a careful re-design of the aluminum component was fundamental to match the HPDC manufacturing process features properly and to maximize weight reduction at the same time. PASC and SSC components have quite a different shape and weight depending on the scenario, but they fulfill the very same safety-relevant functions (in terms of structural and fatigue resistance etc.) on the same vehicle.

In this case study, both primary data, i.e., data taken from the field, and secondary data, i.e., information retrieved from literature and databases (Frischknecht et al. 2005), have been used. In detail, state-of-the-art information can be found with regard to mineral reduction and transformation into hot rolled steel coil (World Steel Association 2010) and primary aluminum ingot (European Aluminum Association 2013), respectively, as detailed at the beginning of this section. However, the following steps of the component's production strongly depend by the specific case study; hence, the use of literature data could lead to misinterpretations. For this reason, an in-depth process analysis was undertaken to take the specific process features into account for both cases, again as described at the beginning of this section. Primary data were then assembled into a comprehensive database thanks to the cooperation of some companies located in northern Italy. This approach was adopted for both the scenarios. In particular, the new aluminum component production has been evaluated through the use of a model developed by some of the authors and explained in a previous research (Cecchel et al. 2016). In each scenario, an amount of either electric energy or heat, depending on the specific features of the different process, has been used in order to evaluate the different phases of the process.

A summary of input/output flows for S1 primary aluminum suspension crossbeam (PASC) from raw material extraction to component manufacturing is shown in Table 1. In detail, the information reported in the first two columns are retrieved from a processing of literature data (European Aluminum Association 2013), while the "component manufacturing" colum refers to primary data.

In Table 2, an input/output overview for S2 steel suspension crossbeam (SSC) from raw material extraction to component manufacturing is reported. In particular, the information reported in the first column are retrieved from a processing of literature data (World Steel Association 2010), while the "component manufacturing" colum refers to primary data.

Table 1 Input/output overview for S1 primary aluminum suspension crossbeam (PASC) from raw material extraction to component manufacturing

	Raw material extraction	Primary ingot production	Component manufacturing
Input			
Bauxite (kg)	52.96		
Aluminum electrolysis product (kg)		12.28	
Aluminum primary ingot (kg)			16.37
Electric energy (kWh)	244.46	25.91	5.83
Heat (MJ)			193
Anode and paste production (kg)	5.40		
Aluminum fluoride (kg)	0.19		
Cathode (kg)	0.08		
Steel (kg)	0.05		
Cryolite (kg)	0.02		
Aluminum scrap (kg)		3.99	
Silicon (kg)		0.39	
Chlorine (kg)		0.001	
Argon (kg)		0.03	
Nitrogen (kg)		0.004	
Output			
Aluminum electrolysis product (kg)	12.28		
Dross (kg)		0.29	
Aluminum primary ingot (kg)		16.36	
Aluminum crossbeam (pcs)			1
Aluminum new scrap (kg)			6.10

Table 2 Input/output overview for S2 steel suspension crossbeam (SSC) from raw material extraction to component manufacturing

	From raw material extraction to hot rolled steel	Component manufacturing
Input		
Dolomite (kg)	0.73	
Ferrous scrap (kg)	4.97	
Iron ore (kg)	56.61	
Limestone (kg)	1.03	
Hot rolled sheet, steel (kg)		41.8
Electric energy (kWh)	289.17	19.63
Output		
Hot rolled sheet, steel (kg)	41.8	
Scrap steel (kg)		12.3
Steel crossbeam (pcs)		1

Table 3 Vehicle data

	Vehicle data
Type	Light commercial vehicle (N1-III)
Engine	90 kW diesel engine
Transmission	Manual
Curb weight (kg)	2350
Tires	265/75 R16

More details about the implementation of the database for the aluminum component production can be retrieved in a previous research (Cecchel et al. 2016).

Regarding the service life phase, the vehicle on focus is a light-duty commercial vehicle (category N1, class III as adopted in the European Directive 2007/46/EC). Since, using a real-world vehicle would lead to a very time-consuming and expansive test campaign. A model developed within of Matlab-Simulink environment (Chindamo et al. 2014b) has been used instead. It has proven to be reliable and effective as it has been successfully used in a previous work (Chindamo

Table 4 European driving cycles used for the purpose of this study

	ECE-15 (urban)	EUDC (extra-urban)	NEDC (mixed)
Length (m)	994	6582	10,560
Avg speed (km/h)	18.35	59.23	31.68
Top speed (km/h)	50	120	120
Time at idle (s/km)	60.36	9.12	5.68

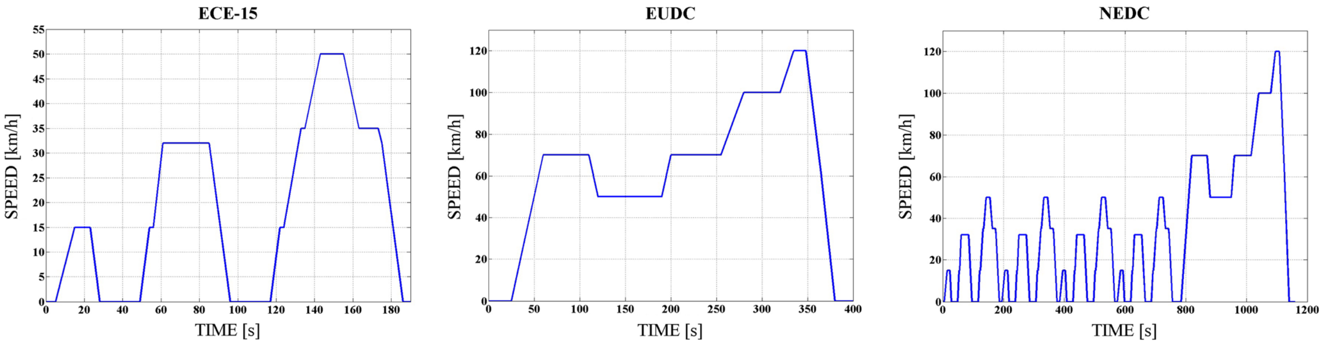

Fig. 3 Graphical representation of the European driving cycles used for the purpose of this study

et al. 2014a). In particular, it estimates powertrain performance, fuel consumption, and exhaust emissions for either traditional and hybrid-electric vehicles along a generic driving cycle. Table 3 reports vehicle data while Table 4 and Fig. 3 show the three European driving cycles (ECE-15, EUDC, NEDC as adopted in the European Directive 91/441/CEE) used to evaluate the weight reduction effect.

The results of the driving cycle simulations are reported in Table 5.

They show that urban ECE-15 cycle is the most demanding in terms of fuel consumption (13.43 l/100 km), and hence generated the highest level of emissions, because it features frequent start and stop maneuvers and the longest time when the vehicle is still with engine at idle, while extra-urban EUDC cycle is the least demanding due to its higher average speed and no start and stops (5.78 l/100 km). Considering the lighter vehicle on the same driving cycles, Table 5 shows a reduction of both average fuel consumption and exhaust emissions of 0.142%, which means that this vehicle running on the abovementioned driving cycles saves 7.67E−02 l/100 km of fuel per 100 kg of curb weight saved.

As stated before, the weight reduction considered in this work regards the replacement of the original steel suspension crossbeam (30 kg) with a specially designed aluminum one (15 kg). Thus, simulation results reported in Table 5 have been carried out on the whole vehicle, and then results have been weighed in order to consider the single-component effect in the "use on LCV" phase.

After that, energy consumption has been calculated considering a diesel calorific value of 9.86 kWh/l over a service life mileage of 350,000 km. It is worthwhile to note that the results presented in Table 5 are related to the reduction of fuel consumption and emissions over 100 km in order to guarantee an easier comparison with the literature data presented in the introduction. Considering the lighter vehicle on the same driving cycles, Table 5 shows a reduction of both average fuel consumption and exhaust emissions of 0.14%/100 km, which means that this vehicle running on the abovementioned driving cycles saves 7.67E−02 l/100 km of fuel per 100 kg of curb weight saved. It is important to highlight that the global emission saving is slightly because it is related to a weight saving of only a component (~ 15 kg saved of the total 2350 kg vehicle weight).

Finally, waste components at the end of the life cycle have been supposed to be collected and recycled for a 95% and disposed in landfill for the remaining 5%, for both scenarios (Das 2000, Kim et al. 2010a). The substitution method was adopted for the allocation of the recycling impacts.

In particular, using the correspondent end of life scenarios integrated in SimaPro software, credits of energy and emissions are considered for the recycling life cycle phase for both aluminum and steel (Das 2000). Indeed, less energy is required to produce metal with recycled metal than with ore.

Table 5 Driving cycles simulation results

	ECE-15 (urban)		EUDC (extra-urban)		NEDC (mixed)		Average	
	Steel	Al	Steel	Al	Steel	Al	Steel	Al
Fuel consumption (l/100 km)	13.43	13.42	5.78	5.77	8.68	8.67	9.30	9.29
CO2 emission (kg/100 km)	31.96	31.93	13.76	13.73	20.66	20.63	22.13	22.10
Fuel consumption and CO2 emission reduction (%/100 km)	− 0.07		− 0.21		− 0.14		− 0.14	
Fuel consumption reduction (l/100 km/100 kg saved)	6.71E−02		8.10E−02		8.21E−02		7.67E−02	

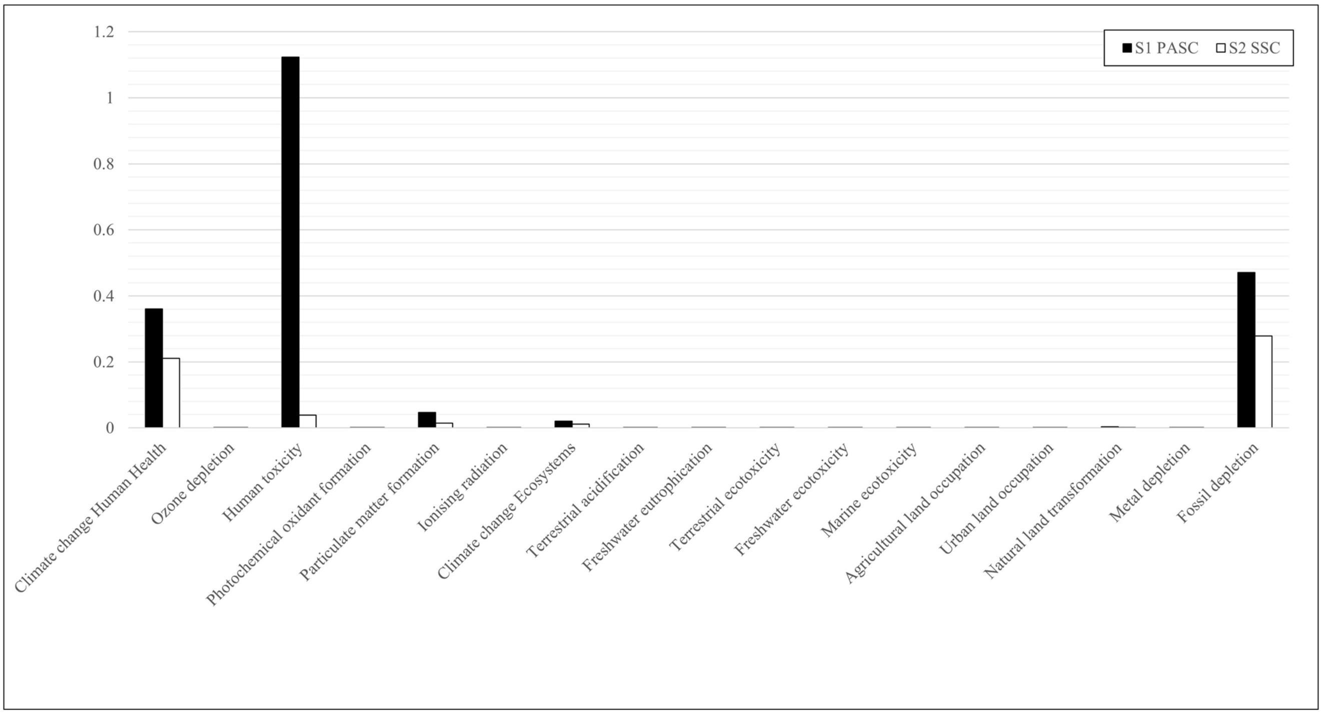

Fig. 4 Normalization results for the two scenarios (PASC vs SSC), from raw material extraction to component manufacturing (the impacts represented are dimensionless)

3 Results and discussion

3.1 Life cycle impact assessment

Based on the inventory, a life cycle impact assessment (LCIA) analysis has been conducted in order to quantify the magnitude of the environmental impact for an aluminum lightweighted (1) and a conventional steel (2) automotive component on the basis of a 350,000 km service life mileage. All calculations were performed using SimaPro V7.3 software with the adoption of the ReCiPe impact assessment methodology (Goedkoop et al. 2009). Figure 4 and Table 6 present the normalization analysis with egalitarian perspective of the component manufacturing's phase (from raw material extraction to manufacturing), for each of two different scenarios. First of all, scenario 1 (aluminum component) presents the highest magnitude of the environmental impact in all the impact categories of the ReCiPe impact assessment method.

Table 6 Normalization results for the two scenarios (PASC vs SSC), from raw material extraction to component manufacturing, for the most relevant impact categories

	S1 PASC	S2 SSC
Climate change human health	0.36	0.21
Fossil depletion	0.47	0.28
Human toxicity	1.12	0.04

Furthermore, both scenarios have a peak in the fossil depletion, climate change, and human health and human toxicity impact categories, which can be explained by the energy demand.

Figure 5 and Table 7 show the normalization analysis with egalitarian perspective for the sole use phase of each component on an LCV with three different European driving cycles (ECE-15, EUDC, NEDC). As can be seen, the most relevant impact was the human toxicity that is mainly due to the air emissions during the combustion of petroleum fuels. The aluminum scenarios' impact is always lower than the steel one that is particularly evident within the most relevant impact category (human toxicity). Among the driving cycles, the urban ECE-15 one had the highest environmental effect, due to the frequent start and stop maneuvers and the longest time when the vehicle is still with engine at idle. The extra-urban EUDC cycle is the least demanding scenario; this is due to a higher average speed and the infrequent occurrence of start and stops. Moreover, the highest benefit of the lightweighting for the component under study occur with the ECE-15 driving cycle, where the percentage reduction of the single score assessment indicator is maximum.

Figure 6 and Table 8 show the comparison of the environmental impacts of the two scenarios (PASC and SCC), considering the whole life cycle, i.e., from raw materials extraction to recycling/disposal. The results are shown for each of the European driving cycles considered for the use phase (ECE-15, EUDC, NEDC) and using normalized mid-point impact categories.

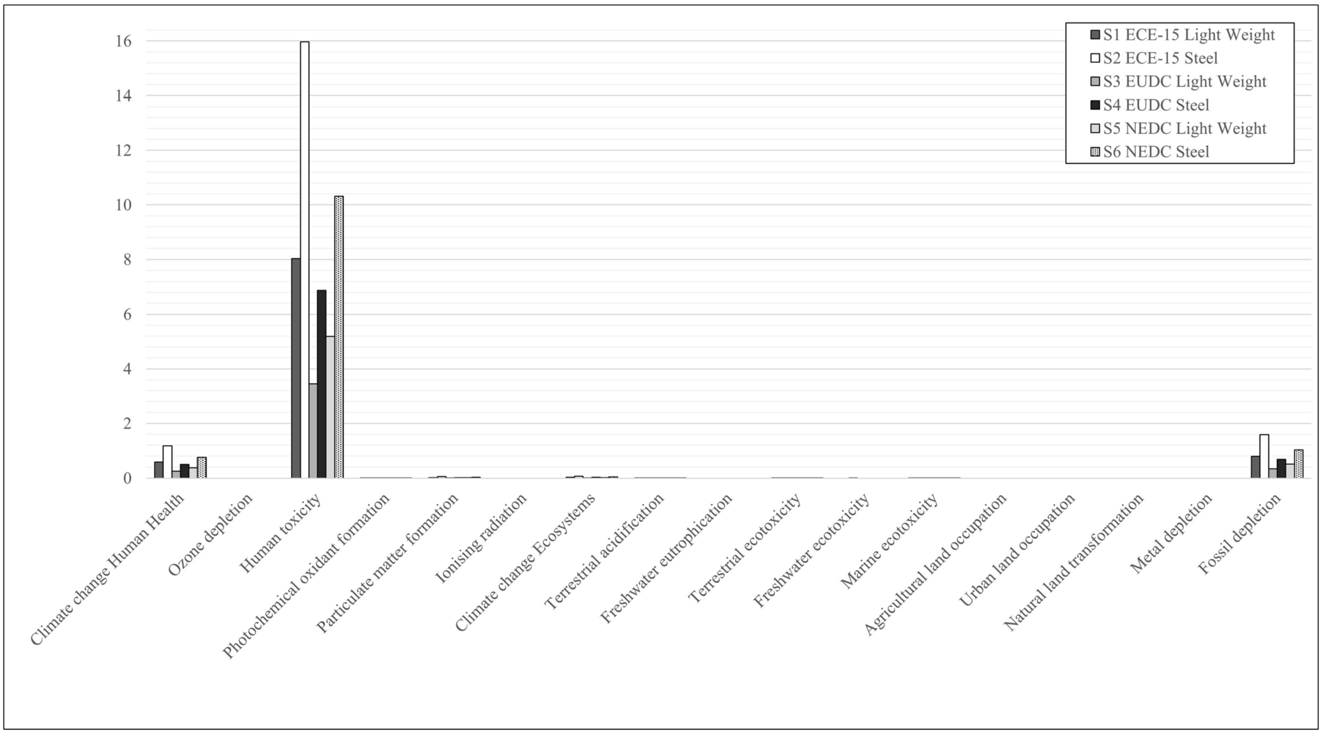

Fig. 5 Normalization result for the six scenarios, for the use of the component on the LCV (the impacts represented are dimensionless)

The most relevant impact was the human toxicity that is mainly referred to the energy consumption and the combustion of fuels. The high energy demand determined also the other most impacting categories, for example, climate change and human health and fossil resources depletion.

In detail, the steel component shows a stronger environmental impact on all the driving cycles. This confirmed that the manufacturing phase impact on the overall life cycle is lower than the service life one, since the latter showed a strongly higher contribution.

In conclusion, during this LCA phase, it was supported the environmental benefits arising from the employment of a commercial vehicle with an innovative lightweight aluminum high-pressure die casting crossbeam suspension in replacement of the conventional heavier steel component.

Table 7 Normalization results for the six scenarios, for the use of the component on the LCV, for the most relevant impact categories

	S1 ECE-15 light weight	S2 ECE-15 steel	S3 EUDC light weight	S4 EUDC steel	S5 NEDC light weight	S6 NEDC steel
Climate change human health	0.59	1.17	0.25	0.50	0.38	0.76
Fossil depletion	0.79	1.58	0.34	0.68	0.51	1.02
Human toxicity	8.03	15.96	3.45	6.87	5.18	10.32

3.1.1 Sensitivity analysis

To study the uncertainty in the output, a sensitivity analysis has been carried out. The analysis has been limited to the EUDC driving cycle as this is the case where using aluminum instead of steel, the percentage reduction of the environmental impact in each impact category is minimum, i.e., where the uncertainty is maximum.

A first analysis is referred to the choice of recycling methodology. In particular, it was analyzed both "closed-loop," which is the use of 100% secondary aluminum alloy after EOL, and the "open-loop," that whereas is represented by the combination among different percentages of primary and secondary aluminum, as shown in Fig. 7. To better understand the analysis, in the graphs are highlighted only the more relevant impact categories (human toxicity, fossil depletion, and climate change human health) while the minor ones (ozone depletion, photochemical oxidant formation, particulate matter formation, ionizing radiation, climate change ecosystems, terrestrial acidification, freshwater eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, agricultural land occupation, urban land occupation, natural land transformation, metal depletion) are reported as "other categories."

It is worthwhile to note that, in this analysis also the examined case (5% primary aluminum and 95% of

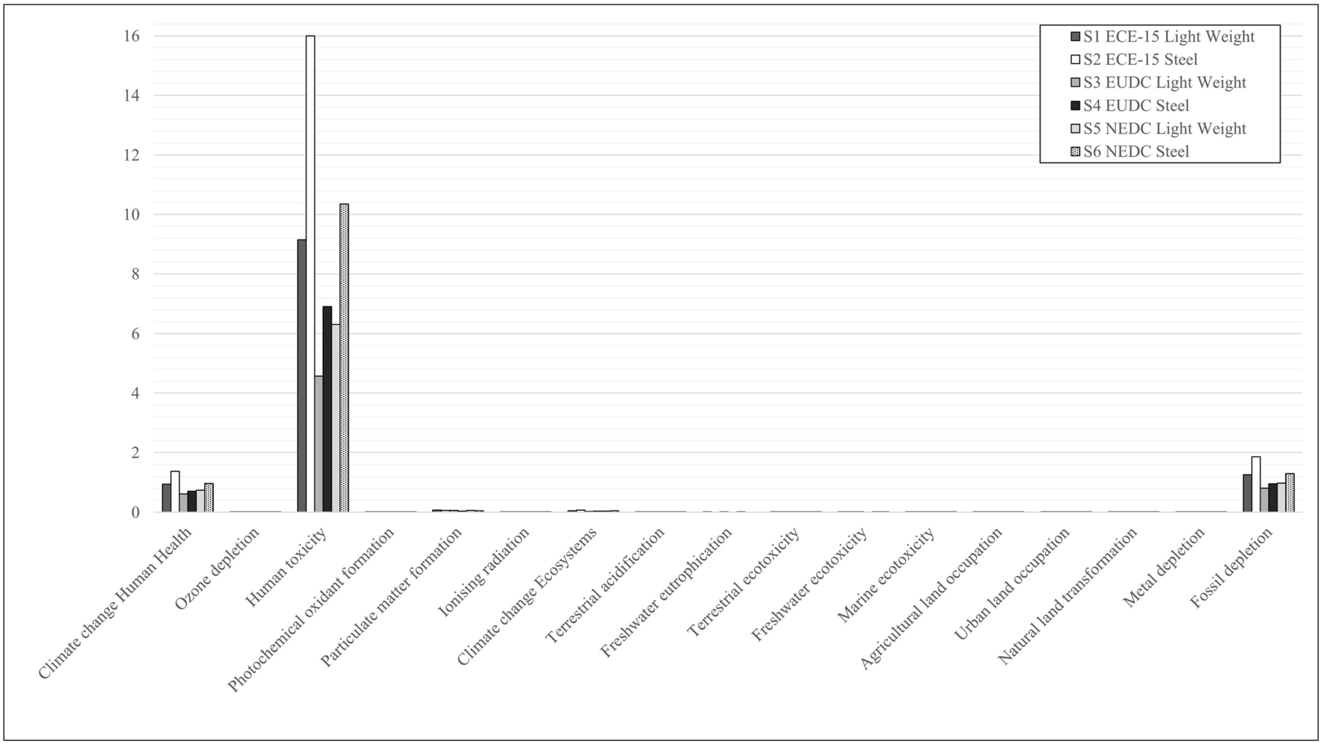

Fig. 6 Normalization results for the six scenarios, for the whole life cycle (the impacts represented are dimensionless)

secondary aluminum) and the comparison with the traditional steel solution have been considered. The single score obtained with the RECIPE impact assessment method was used for the analysis. The results of the comparison among the different recycling methodologies confirmed that the highest environmental benefit was given by the closed-loop scenario, as expected. Anyway, it is highlighted that also the impact of the other mixed aluminum scenarios was always deeply lower than the traditional steel solution. Indeed, the EOL phase had a low impact on the overall life cycle and therefore the difference among the baseline (steel) and the various aluminum scenarios are slightly influenced by the recycling methodology choice. Finally, it is also important to evidence that in Fig. 7 is reported even the case studied during the present work and the same considerations are confirmed.

Table 8 Normalization results for the six scenarios, for the whole life cycle, for the most relevant impact categories

	S1 ECE-15 light weight	S2 ECE-15 steel	S3 EUDC light weight	S4 EUDC steel	S5 NEDC light weight	S6 NEDC steel
Climate change human health	0.95	1.38	0.61	0.71	0.74	0.97
Fossil depletion	1.27	1.86	0.81	0.96	0.98	1.30
Human toxicity	9.15	16.00	4.57	6.91	6.31	10.36

In addition, to further characterize the sensitivity of the results with respect to the uncertainty of the whole set of the inventory data, a Monte Carlo analysis has been performed. With the Monte Carlo analysis, the inventory parameters are transformed into stochastic variable with a log-normal distribution. The standard deviations of the distribution have been taken from the Ecoinvent database, and the log-normal distribution was adopted as it is widely used in literature (Frischknecht et al. (2005) for Monte Carlo analysis in the context of LCA case studies). The inventory data are then randomly sampled, and the impact assessment method is applied for a certain number of combinations. Also in this case, the Monte Carlo analysis has been applied to the comparison of the EUDC scenarios.

The results obtained are shown in Fig. 8, where, for each impact category, the probability for scenario 3 EUDC to have a higher environmental impact then scenario 4 EUDC (and vice versa) is represented. As can be seen, for the three most affected impact categories, i.e., climate change, human health, human toxicity, and fossil depletion, the probability for scenario 4 EUDC to have a higher environmental impact then scenario 3 EUDC is higher than vice versa.

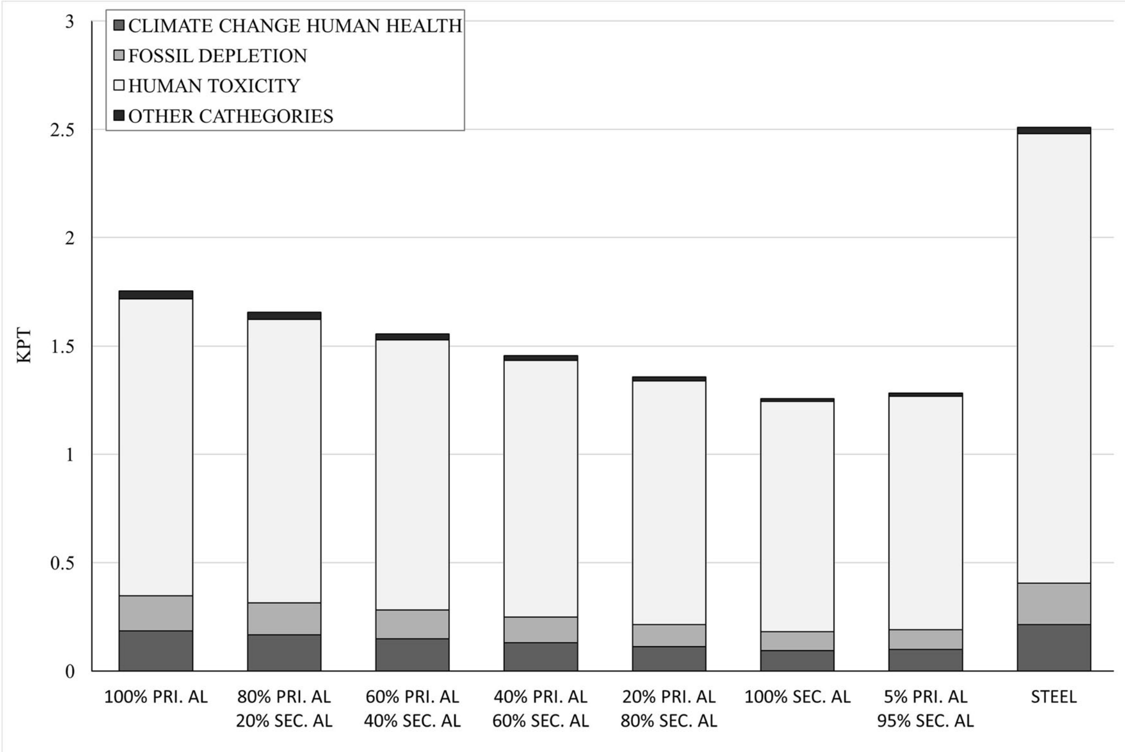

Fig. 7 Sensitivity analysis around the choice of recycling methodology

4 Conclusions

The present study examined the environmental benefits associated with the production of lightweight components and with their use on commercial vehicles. In particular, a safety-relevant component (a suspension crossbeam) for CVs has been analyzed and a comparison between the innovative one-piece high-pressure die casting aluminum component (PASC, scenario 1, 15 kg weight) and the conventional steel sheet metal part (SSC, scenario 2, 30 kg weight) has been

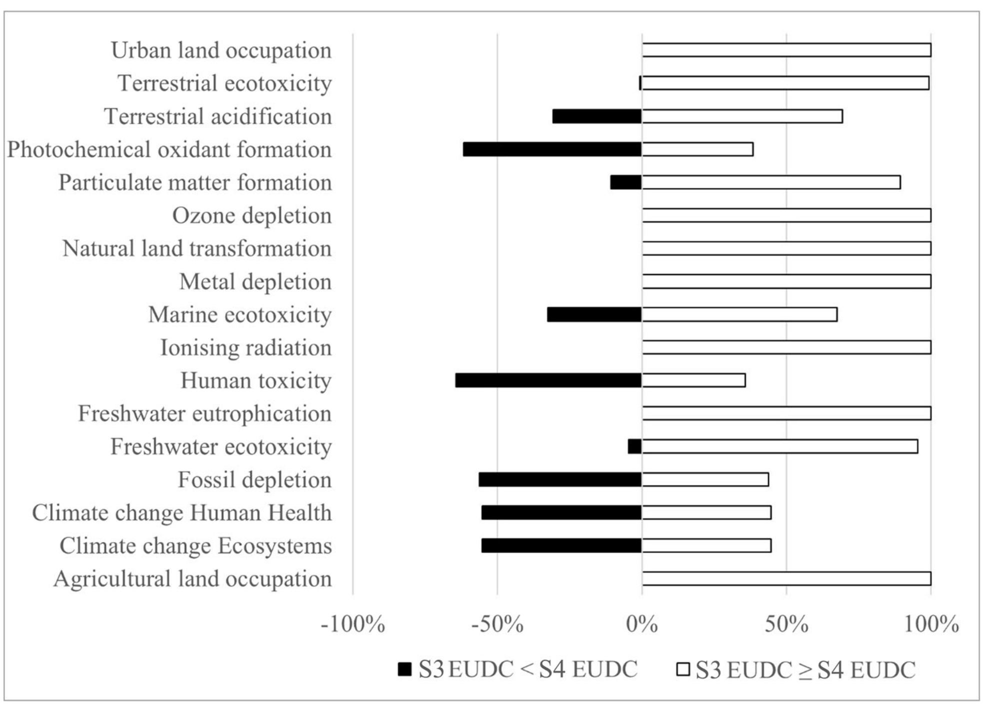

Fig. 8 Results of the Monte Carlo analysis applied to the comparison of scenario S4 EUDC

performed through a comparative LCA "from cradle to grave." Considering the manufacturing phase (from raw material extraction to component manufacturing), the highest impact was observed in scenario 1. This is mainly caused by the large electricity and heat demands for the liquid aluminum electrolysis, followed by the component casting energy consumption. This last item highlights the relevance of a detailed analysis of each foundry phase through the use of actual industrial (i.e., primary) data in order to avoid underestimated results. Anyway, the manufacturing phase has a low impact on the overall life cycle, since the vehicle use stage showed a strongly higher contribution. Actually, this LCA phase confirmed the benefit given by the use of the particular redesigned aluminum component which has been described during this study in substitution of a heavier component for LCV applications. In particular, the urban ECE−15 cycle had the highest environmental impact, while the extra-urban EUDC cycle is the least demanding. It is important to highlight that the global emission saving in comparison with the total fuel consumption and emissions of the entire vehicle is slightly because this analysis is related to a weight saving of only a component (~ 15 kg saved of the total 2350 kg vehicle weight) in order to evaluate in detail its overall LCA. A future extension of the lightweighting up to the estimated trend of 20% weight saving reported in the introduction would lead to even higher benefit. A sensitivity analysis was also performed in order to evaluate the uncertainty of data used in the different scenarios, which confirmed the results obtained. In conclusion, the present research demonstrated the environmental benefits arising from the employment of a commercial vehicle with an innovative lightweight aluminum high-pressure die casting crossbeam suspension in replacement of the conventional heavier steel component.

Acknowledgements The component object of the study has been developed by Streparava SpA. The authors are grateful to Streparava SpA and Mr. Antonio Gandellini for the support in providing data.

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