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Life Cycle Sustainability Assessment: application to the automotive sector and challenges for the lightweighting

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Summary

The scientific community, as well as the industrial sector, is demonstrating a growing interest in evaluating sustainability by taking into account the “three-pillar” concept: environment, economy and society. The Life Cycle Sustainability Assessment (LCSA) methodology, a combination of LCA (environment), LCC (economy) and S-LCA (society), has been selected among others.

The research project aims at contributing to the development of LCSA by adopting a sector-specific approach as opportunity to enhance the practicability of the methodology among organizations and strengthen its role as a decision-support and strategic tool. This thesis represents one of the first work dealing with the sustainability assessment of products by means of the LCSA in the automotive sector in the context of the early design phase of automotive components in a lightweight perspective. In particular the research focuses on the LCSA applicability in the context of lightweight design in the automotive sector. Both methodological aspects and data availability have been addressed to contribute to the operationalization of the LCSA methodology, and the main research questions regard:

- LCSA applicability to the lightweight design;
- The state-of-the-art of LCSA and S-LCA in the automotive sector in terms of knowledge, applications and needs;
- S-LCA methodological settings regarding goal and scope and inventory analysis;
- The state-of-the-art of approaches and (mathematical) methods to integrate environmental, economic and social results;
- The data availability for LCA and LCC studies concerning innovative materials and related technologies for component lightweighting.

To answer the above stated questions this research has been structured following two pathways: the first dedicated to the methodological challenges that emerged from the state of the art of LCSA and related methodologies (LCA, LCC and S-LCA); the second focused on the data availability and data gathering as a relevant aspect to foster the methodology progress and spread. Works on LCA applied to the lightweight design have been reviewed with the aim of identifying the most important advantages/disadvantages caused by the substitution of traditional materials with lighter ones. The current available databases, in particular GaBi, were reviewed to identify available dataset concerning materials production (polymers, fibres, metals), technologies dedicated to metals and composites manufacturing, and processes for the End-of-Life (EOL) treatment of vehicles/components and materials recycling. The review of LCC study has been driven by the need of identifying the awareness level and spread of LCC applications in the automotive sector, and lightweight design in

particular; how and if the methodological elements described by the Code of Practice are addressed. As far as S-LCA is concerned, the reviewed papers have been analysed and discussed in terms of key elements affecting the goal and scope and inventory phases of the S-LCA case studies. Those elements have then been organized into a conceptual map to guide practitioners during the application. The review of LCSA studies was mainly focused on methodological setting able to guarantee appropriateness of goal and scope definition within a sustainability framework, and approaches and mathematical methods to integrate results. Furthermore, a number of case studies have been carried out within the framework of the EU-project ENLIGHT and together with Magneti Marelli®. Those studies gave the possibility of collecting primary data and modelling several design solutions for different kinds of vehicle parts (i.e. door, suspension system) and propulsion systems (electric and internal combustion engine), as well as the possibility of presenting and interpreting results with companies directly involved in the component production. Additionally, activities dedicated to stakeholder engagement have been proposed; in particular on-site visits and an online survey targeted to prioritize a set of sustainability indicators to be used in the LCSA. In the automotive sector, as in all the sectors where innovation and sustainability are key drivers for competition, results of applications of LCSA and related methodologies are strictly confidential, and consequently not publicly available. For this reason, this research included only publically available studies and procedures, and discussions and conclusions are representative for published sources and activities directly developed within this thesis.

A delicate trade-off was observed between environmental benefit in the use stage and impact increase in the production stage; this is particularly evident when the lightweight design is applied in electric vehicles. Results from the case studies supported the idea that vehicle propulsion system and material pairs are the design elements mostly influencing the final results. This relationship was furthermore evaluated by means of the break-even point and $\Delta_{I/M}^{P}$ indicators, representing the vehicle's life distance the lightweight solution could give environmental benefit if compared to the reference one and the ratio between delta mass and delta impact of a set of impact categories respectively. The weight reduction leads to improvements in terms of fuel consumption and positively affects those environmental impact categories where the use stage is more involved (i.e. GWP, PED), whereas indicators mostly affected by the material stage were found to worsen. The importance of enlarging the environmental assessment to a diverse set of impact categories, in addition to the CO_2 emissions typically addressed in the sector, was then highlighted. Since a limit coverage of specific materials and processes was found in the GaBi database, a desk research and data gathering in collaboration with OEMs allowed collecting a number of data (i.e. energy consumption, scraps production) regarding: composite, manufacturing technologies and EOL processes.

The literature review of LCC in the automotive sector showed that the evaluation of economic feasibility of lightweight solutions struggles with the complexity of the product (number of materials, processes and actors involved) and the lack of specific standard. As a consequence the research project focused on key methodological aspects. First, the environmental LCC type was selected as the most appropriate to make LCC consistent in the framework of a LCSA study. The decision of whether implementing a lightweight solution does make sense only if the production cost is compared with the benefits that this solution will produce in the use stage (in favour of the consumer); for this reason a 'hybrid perspective' was proposed and discussed. Additionally, a clear list of cost categories, in particular information regarding manufacturing processes, was developed, also in collaboration with an automotive manufacture, and was validated by a real case study. It was observed that steel replacement with carbon fibres composite is responsible for an increase of the product cost (high material cost and the high cycle time production), which is not balanced by the fuel cost reduction. Furthermore, the case study suggested that the CO_2 emissions cost is negligible if compared with other costs.

The key elements affecting the goal and scope, and inventory phases of S-LCA were dealt with (i.e. functional unit, system boundaries, perspective) and placed into a conceptual map. They were grouped into seven nodes representing a crucial point where a decision needs to be taken in order to carry out the analysis. The nodes are then placed into a four-step procedure representing a suggestion for an orderly procedure of analysis. The conceptual map was then analysed with respect to the automotive sector, with the ultimate goal of contributing to the development of the S-LCA methodology tailored to the peculiarities and needs of the sector. Additionally, the social indicators proposed by the UNEP/SETAC methodological sheets were analysed together with those proposed by the Roundtable for Product Social Metrics initiative. The list from the quantitative approach of the Roundtable initiative was selected as the starting point for testing the main challenges in terms of data gathering and data allocation.

The Multi-Criteria Decision Analysis (MCDA) was identified as a suitable approach to integrate LCA, LCC and S-LCA results; in particular the TOPSIS, combined with fuzzy set approach, was selected. This choice was mainly guided by the applicability of such method, in relation to others, and its documented use in the automotive sector. An online survey, targeted to experts from the automotive sector, both industry members and researchers, and people working in the field of sustainability and Life Cycle Assessment, was carried out to prioritize a set of quantified social, economic and environmental sustainability indicators

All the arguments presented throughout the thesis were then integrated and applied to LCSA case studies regarding two vehicle components (knuckle and dashboard). First, the goal and scope was defined according to the proposed conceptual map, thus providing further insights for tailoring the map to the sector. The data inventory was developed according to the quantitative approach of the Roundtable for Product Social Metrics initiative, in particular the main companies involved in the production stage were involved. Social data were elaborated according to the Type I method proposed by the Roundtable, in which data allocation is followed by aggregation and referencing. The TOPSIS method was applied to integrate, compare and rank the two design solutions for a dashboard according to the weights criteria derived from the survey. Overall, such method was proved applicable although both advantages and limits were identified. Its use is strictly linked to comparative analysis therefore other approaches need to be used in the case of absolute analysis as in the case of the knuckle study. The TOPSIS method allowed to define the best alternative also when a high number of indicators are used since the mathematical operations and data could be easily handled in an Excel programmed workbooks. Moreover it could provide results at different levels, thus allowing the identification of potential trade-off. However, the high number of indicators used could hinder the final interpretation in terms of impacts and possible technical solutions. In this sense, limiting the number of indicators could improve the effective use of the method during an early design phase when decisions need to be taken. Also the survey was found a practicable way to identify the priority level of a set of sustainability criteria and its use in combination with the MCDA was found an effective way to enhance stakeholder involvement in the sustainable design context.

Finally, this thesis identified and proposed the opportunities for future research works to enhance LCSA application in the automotive sector.

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Acronyms List

ADP$_{el.}$: Abiotic Depletion Potential elements
AP: Acidification Potential
ASR: After Shredding Residues
BiW: Body-in-White
CF: Carbon Fibre
eLCC: Environmental LCC
ELVs: End-of-Life Vehicles
EOL: End-of-Life
EP: Eutrophication Potential
EV: Electric Vehicle
FAEP: Fresh-water Aquatic Ecotoxicity Potential
FRV: Fuel Reduction Value
FU: Functional Unit
GF: Glass Fibre
GHG: Greenhouse Gas
GWP: Global Warming Potential (100 years)
HGM: Hollow Glass Microspheres
HTP: Human Toxicity Potential
ICE: Internal Combustion Engine
LCA: Life Cycle Assessment
LCC: Life Cycle Costing
LCIA: Life Cycle Impact Assessment
LCS: Life Cycle Stage
LCSA: Life Cycle Sustainability Assessment
MAETP: Marine aquatic Ecotoxicity Potential
NEDC: New European Driving Cycle
ODP: Ozone Depletion Potential
OEMs: Original Equipment Manufacturers
PA: polyamide
PED: Primary Energy Demand
PLC: Product Life Cycle
POCP: Photochemical Ozone Creation Potential
PP: polypropylene
S-LCA: Social Life Cycle Assessment
TEP: Terrestrial Ecotoxicity Potential

Preface

This research represents one of the first examples of Life Cycle Sustainability Assessment application to the lightweight design in the automotive sector. Beside an extensive literature review, mostly dedicated to identify the starting point of Life Cycle Sustainability Assessment (LCSA) and Social Life Cycle Assessment (S-LCA) in the automotive sector, this work provides contributions regarding S-LCA implementation and integration of results in the LCSA. Moreover, also LCA and LCC have been addressed as a way to find out environmental and economic issues related to lightweight solutions to be conveyed in the LCSA framework

S-LCA was developed according to the methodology proposed by the Roundtable for Product Social Metrics initiative, and this represents another innovative element of this research that applied the social quantitative approach as the first case in the automotive sector.

Moreover, an interesting contribution is given by the number of real case studies which involved LCA, LCC, S-LCA and LCSA evaluations. The relevance of this research is also provided by the substantial collaboration with the majority of Europe's automotive OEMs (original equipment manufacturers) that have been involved both in the data collection, and results discussion. In some case companies were involved in the discussion about the role that LCSA might play in the early design phase of vehicle components, especially when lightweight solutions are explored.

Finally, a contribution also regards the data availability increase, particularly for what concern environmental data for innovative materials, and related manufacturing technologies, in the lightweighting context.

1. Introduction

1.1. Research framework

The automotive is considered a sector on the rise. In 2010 global vehicle registrations were estimated around 1.015 billion of units (Ward’s auto 2016) and this number is expected to grow up to 2.5 billion by 2050 (ITF 2015). Much of this growth is foreseen to occur in emerging markets such as China and India (ITF 2015), and it will result in significant increases in air emissions, global fuel demand and material requirements, and a corresponding increase of waste produced during the End-of-Life (EOL) is expected (Berzi et al. 2013). Thus, decisive actions and initiatives are necessary to foster an industrial renaissance rooted into the sustainability concept, as promoted by the European Commission (EC 2014).

The automotive sector is a complex network of companies which work at different levels of the production stage of a vehicle, vans, trucks and caravans from the materials production to the final product sale, material recovery and disposal.

The sector consists primarily of vehicle makers that own and manage large manufacturing plants where the production of some parts and the assembly lines are carried out; meanwhile material suppliers, the technology developers and components producers make up another relevant part. The automotive industry is considered highly capital and labour intensive. The European automotive industry is central to Europe's prosperity since it is among the world's largest producers of vehicles: it is a huge employer of skilled workforce, a key driver of knowledge and innovation, and represents the largest private investor in research and development (ACEA 2015a).

Meanwhile, vehicles are responsible for large-scale environmental and socio-economic impacts at every life cycle stage: raw material stage, characterized by intensive resources and energy consumptions; use stage, affecting global fuel demand, air pollutants emissions, noise and road accidents; EOL involving complex waste management systems (Jasinski et al. 2015).

In the last years the R&D investments have been related mainly to environmental sustainability of new products and social sustainability of companies and related supply chains, which are perceived as the key factor for company’s public reputation and attractiveness on the market (Koplin et al. 2007) as they are generally considered responsible for the environmental and social impacts caused by their supplier.

1.1.1. Regulations

In Europe the environmental ***regulation*** (e.g., 2009/125/EC - Energy related products-ERP, 2009/443/EC - CO2 emissions from light-duty vehicles, 2000/53/EC – End-of-Life vehicle – ELV) is a key driver for promoting the eco-innovation in the sector, leading to the development of new materials, and related technologies, able to reduce the environmental impact of vehicles and their components. Yet, pressure from stakeholders and Corporate strategies towards sustainability are the main drivers for the performances improvements of products within a wider sustainability (Andriankaja et al. 2015; Pallaro et al. 2015).

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

- Reduce tailpipe emissions hence reduce Greenhouse Gasses effect and improve air quality;
- Increase efficiency and hence reduce consumption of energy and natural resources;
- Increase recyclability and recoverability of vehicle parts thus reducing landfilled waste (Subic and Koopmans, 2010).

The recent Directive 2014/95/EU on disclosure of non-financial and diversity information by certain large companies and groups could lead the companies to disclose information on policies, risks, and outcomes as regards also social matters, and employee related aspects, respect for human rights, anti-corruption, and bribery issues.

1.1.2. Social issues in the automotive sector

Several initiatives exist concerning ***social issues***. The reporting of social performances within the automotive sector is a well-rooted activity at corporate level. The Corporate Social Responsibility (CSR) is a major approach in the assessment of social performance of companies, widely used for four main reasons: i) it is supported by many emerging normative measures (standards, certification, codes of conduct, rankings) (EC - European Commission 2011; EC - European Commission 2014b); ii) it has a tripartite dimension that embraces all the stakeholders: organizational (business practices), academic (theoretical formalization) and political (governance); iii) it allows for a clear and effective communication to different target audience; iv) it is the place where social, environmental, ethical, human rights and consumer concerns can be integrated in the business operations and strategy by collaborating with stakeholders, thus providing a broad overview of the organisation behaviour and attitude beyond the social aspects (EC - European Commission 2011).

CSR in the sector includes a variety of issues along the whole life cycle, ranging from alternative technologies and fuels to the supply chain and EOL management. The most frequent CSR activities are based on the International Labour Organization (ILO) code, with focus on essential working conditions, companies' individual codes of conduct, Global Reporting Initiative (GRI) standards, supply chain responsibility, and environmental management systems (Martinuzzi et al. 2011).

The GRI is a voluntary standard that provides a reporting framework for companies that want to communicate about their supply chains sustainability by means of a set of economic, social and environmental indicators (Global Reporting Initiative 2015). Since different sectors have been recognized to face specific sustainability issues, a GRI's Sector Guidance has been developed: for the automotive one, a sector guidance in pilot version has been proposed but not finalized yet (Global Reporting Initiative 2015).

While many initiatives have been undertaken by single companies, a collaborative effort within the automotive sector has been launched with the "Self-Assessment Questionnaire on CSR/Sustainability for Automotive Sector Suppliers". Subscribed by a number of car manufacturers, the questionnaire is designed to be a first step for suppliers' performance assessment on CSR that all the members of the European Automotive Working Group on Supply Chain Sustainability will apply. It accounts for expectations towards business ethics, working conditions, human rights, and environmental leadership, for tier 1 suppliers[1] as well as their subcontractors and tier n suppliers. As for the social aspects, the questionnaire requires answers about: policy and management system to manage social issues (e.g., respect for human rights, forced or compulsory labour, child labour, working conditions, freedom of association) according to international standards (e.g., ISO26000, SA8000); social audits; health & safety policy and management system; policy regarding business conduct and compliance (corruption, extortion, bribery). This initiative is quite relevant as it sets common and standardised requirements in reporting social issues of concern within the organisation and beyond, and thus it is an important step towards the definition of shared, harmonized and robust indicators.

This questionnaire is expected to be used within a supplier sustainability assessment procedure and to activate a process of evaluation down to the supply chain of a company (ACEA 2015b). It represents the first concrete example of a common, and shared and sector-specific action, to enlarge the sustainability concept boundaries from the single organization level (both corporate and site/plant level) to the whole supply chain, embracing the life-cycle approach.

Moreover, the sector is at the forefront in applying new approaches and methodologies such as S-LCA (UNEP/SETAC 2009) and LCSA (Braithwaite 2001; UNEP/SETAC 2011; Traverso et al. 2013; Salvado et al. 2015). The main reasons of that can be ascribed to some peculiarities of the sector:

- Complexity of product (Mathieux et al. 2008; Golinska and Kosacka 2014);
- High raw material exploitation (i.e., metals, biomaterials/ biopolymers) (Edwards 2004; Sullivan et al. 2013);
- Globalized and high number of value chain actors (Peiró-Signes et al. 2014);
- Complexity of the supply and value chains, which involves both big companies (car manufacturers and OEMs) as well as SMEs (supply chain) (Blume and Walther 2013; Simboli et al. 2014).

As far as the S-LCA is concerned, the automotive sector was among the founders of the recent Roundtable for Product Social Metrics initiative, coordinated by PRé Consultant, aimed at developing a practical and consensus-based methodology for organisations to assess the social sustainability of products[2] (PRé Sustainability 2015).

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[1] Tier 1 suppliers are those who supply materials or components directly to the Company.

[2] The methodology proposed within the Roundtable for Product Social Metrics initiative tries to indirectly tackle social impacts of the existence of the product on stakeholder groups throughout its life cycle by including social topics and

1.1.3. Challenges and methodologies for the automotive sector sustainability

The car manufacturers have been implementing several technical solutions to meet legislation requirements and corporate strategy towards sustainability, and satisfy consumer expectations; examples of these strategies include mass reduction, aerodynamics improvement, conventional internal combustion engines efficiency, safety improvements, alternative propulsion systems, etc. (Jasinski et al. 2015).

Lightweight design is one of the main concern for OEMs since it is proved to produce effective fuel demand reduction and tail pipe emission abatement. It can be achieved by reducing weight through material substitution, coupled with vehicle component redesign, while maintaining vehicle size and so satisfying consumer demand. It is strongly related to material selection, advancements in materials research and related manufacturing technologies. However, the material selection process needs to balance many aspects - technical performances and feasibility, materials recyclability, environmental impact of material production – and this leads to necessarily face controversial issues and trade-off (De Medina 2006; Raugei et al. 2015; Andriankaja et al. 2015; Kelly et al. 2015). New metals alloys, bio-polymers and bio-composites are seen promising alternatives to traditional materials; nevertheless, although the environmental consequences of such strategies have being studied since recent years, the socio-economic results along the supply chain are expected but not yet approached.

The awareness and need for a wider sustainability approach where environmental evaluations are combined with economic and social ones to give a deeper insight for selecting the best trade-off among the three dimensions of sustainability is arising among scientific community, as well as the industrial sector. This, in turn, brings to consider a large number of conflicting environmental, social and economic factors (Schmidt and Taylor 2008; Pallaro et al. 2015; Jasinski et al. 2015).

Within this framework, the Companies need effective and transparent measurement tools to manage all of the economic, social and environmental impacts of their decisions at an early design phase of new products in order to make the best choice.

In the automotive sector the design phase is considered one of the most critical stage since any decision would have economic, environmental and social impacts affecting several stakeholders’ groups encountered along the product life cycle.

Determining which methods are the best candidates to achieve the environmental sustainability lightweight solutions was addressed in literature; within the Design-for-Environment, several methods and tools are applied by designers (e.g. full LCA, LCA-based tools, Matrix-based tools, Guidelines, Checklists, Eco-design guides, Parametric tools and Solution Decision-making tools) (Mayyas et al. 2012a; Andriankaja et al. 2015). The important features of eco-design tools can be summed up in the following points: (1) to be able to quantitative compare different product concepts and (2) to provide improvement options such as alternative materials or processes (Andriankaja et al. 2015). When socio-

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performance indicators that reflect positive and negative impacts of the product. The procedure to allocate the general organizational performance to the product level is clearly described in the handbook.

economic sustainability is even assessed, then the capability of handling complexity of analysis in a transparent way is another important feature.

Several methodologies have been developed during the last years to measure sustainability of products (Hoogmartens et al. 2014); although life cycle-based methodologies are generally considered valid approaches, many research questions exist to make them fully applicable and totally integrated in the design process. As far as the product is concerned, Pallaro et al. (2015) provides a review, targeted to the automotive sector, of works on sustainable production stage (i.e. raw materials, components production, vehicle assembly and vehicle distribution) and consumption stage (i.e. vehicle use and End-of-Life). The majority of such studies includes two dimensions, generally economic and environmental ones, and only a minor part faces social issues. The social dimension is mainly considered during the consumption stage (use and EOL) which is perceived more relevant due to the high number of stakeholders' involved in the air pollution generated by private vehicles and waste discarded by consumers EOL (Pallaro et al. 2015). Indeed the growth of consumers and society awareness is considered one of the most important reason pushing companies to consider social dimensions along all the life cycle of their products and activities.

The adoption of Corporate Social Responsibility policy is already spread among OEMs, as demonstrated by the high number of sustainability report; currently, the Triple Bottom Line and the Global Reporting Initiative (GRI) are claimed to be applicable approaches for calculating sustainability index at organization level (Salvado et al. 2015).

Within the automotive sector literature, (Jasinski et al. 2015) proposes the Full Cost Accounting (FCA) concept as a practical tool to deal with the complexity of triple bottom line decisions in the automotive environment. The application of this method relies on techniques for impacts monetization in order to include and relate internal and external sustainability impacts by means of the unique monetary metric. The Cost–Benefit Analysis (CBA) is another approach generally used for evaluating the attractiveness of projects considering their financial, environmental and social concerns. Although CBA is devoted to include all three dimensions, typically only one or two aspects are taken into account, for this reason different sub-approaches can be observed focusing on one or more of these concerns (Hoogmartens et al. 2014). Other initiatives or studies can be found in literature regarding criteria for evaluating sustainability of products and technologies, which do not refer to a specific accounting method but which share some common aspects with the aforementioned techniques (Blok et al. 2013; van Haaster et al. 2013).

1.1.4. Life Cycle Sustainability Assessment

The ***Life Cycle Sustainability Assessment*** (LCSA) is introduced as a comprehensive sustainability assessment of products and processes along their whole life cycle. LCSA refers to evaluation of all environmental, social and economic negative impacts and benefits in decision-making processes toward more sustainable products throughout their life cycle (UNEP/SETAC 2011). It is clearly a life cycle-based methodology which integrates the three techniques LCA, LCC and S-LCA to represent the environmental, economic and social dimension respectively (Finkbeiner et al. 2010).

It has been claimed to be one of the most common method for assessing sustainability of products and processes and then to support the product related decision-making based on a life cycle perspective and the consideration of the three sustainability dimensions (environmental, economic and social) (Neugebauer et al. 2015).

According to (Guinée 2016), two basic approaches exist. The first, proposed by (Kloepffer 2008; Finkbeiner et al. 2010), promotes LCSA (assessment) as a broadening of ISO-LCA to also include economic and social aspects; it is based on the “triple bottom line” model, also called “three-pillar”, and relies on the scheme:

$$LCSA = LCA + LCC + SLCA$$

where:

- LCA is the environmental Life Cycle Assessment, defined and standardized by the ISO 14040–44 (ISO14040 2006; ISO14044 2006);
- LCC is the environmental Life Cycle Costing or the assessment of economic factors along the product life cycle (Hunkeler et al. 2008; Swarr et al. 2011);
- SLCA (S-LCA in the following) is the evaluation of the social aspects (UNEP/SETAC 2009).

The second approach, proposed by (Guinée et al. 2011), promotes LCSA (analysis) as a transdisciplinary integrated frameworks of models to broaden the scope of current LCA from environmental impacts only to all three dimensions of sustainability, and to deepen the analysis at different level (products, sector and economy), taking into account technological, economic and behavioural relations, just to mention some (Guinée 2016).

Both approaches have the common intent of broadening the impacts analysis from the environmental impacts to the economic and social ones; however they differ in terms of conceptual structure and modelling principles (Sala et al. 2013). The LCSA (analysis) framework merges inventory analysis and impact assessment into one modelling phase; it could address different level of analysis (i.e. product, sector) and level of deepening, whereas the LCSA (assessment) framework is more devoted to applications at the product levels, in line with the applications of the three methodologies LCA, LCC and S-LCA (Sala et al. 2013).

The majority of LCSA case studies published so far have focused on the scheme proposed by (Kloepffer 2008), and addressed its applicability and practicability along with evaluating what kind of information can be obtained and how they can support the decision making process (Zamagni et al. 2013; Guinée 2016). Therefore, this approach will be followed and investigated in the present research.

1.1.5. Projects framework

This research has been developed within the framework of European project and collaborations with OEMs. In particular, environmental assessment was mainly developed within the framework of the EU-project ENLIGHT[3] whose aim is to advance highly innovative lightweight material technologies for application in structural vehicle parts of future volume produced Electric Vehicles (EVs) along four axes: performance, manufacturability, cost effectiveness and lifecycle footprint (Bein et al. 2016). The ENLIGHT project is interconnected with past and running initiative on lightweight technologies (particularly ALIVE project (ALIVE - SEAM 2012)). The main objectives of

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[3] http://www.project-enlight.eu/

ENLIGHT deal with innovative lightweight and low embodied CO_2 materials and manufacturing technologies enabling significant weight reduction for five modules of an EV: Front module, Cockpit and Firewall, Central floor section, Sub-frame and suspension, and Doors/enclosures.

Moreover, a collaboration with Magneti Marelli®, first mainly focused on the environmental assessment of several design solutions of different vehicle systems, was then enlarged also to economic and social assessments, thus providing the opportunity to examine potentials and criticisms of the life cycle-based methodologies during the design phase of new components and collecting primary data.

Then a mirror project of the Roundtable for Product Social Metrics[4], in collaboration with Magneti Marelli and another automotive manufacturer, gave the opportunity to test social indicators and method proposed in the Handbook (PRé Sustainability 2014) and collect data from companies involved in the supply chain of a real component.

1.2. Research questions

The research aims at contributing to the development of LCSA applicability in the context of lightweight design in the automotive sector.

The scientific community, as well as the industrial sector, are demonstrating a growing interest in evaluating sustainability by taking into account the “three-pillar” concept: environment, economy and society. The Life Cycle Sustainability Assessment (LCSA) methodology, a combination of LCA (environment), LCC (economy) and S-LCA (society), has been selected among others (UNEP/SETAC 2011).

From the methodology point of view, despite some initiatives at international and national level, LCSA still presents many open issues which need further progress for the full operationalization of the methodology. Overall, the following matters are some of the critical aspects mentioned in literature about methods for sustainability assessment: i) complexity of analysis and not uniqueness of the final results interpretation (Mayyas et al. 2012a; Andriankaja et al. 2015); ii) many available indicators limiting the practical implementation (Andriankaja et al. 2009; Neugebauer et al. 2015); iii) data availabilities and huge amount of data required (Andriankaja et al. 2015).

Taking inspiration from these elements, this research would contribute to answer to the following questions:

1. **What are the main drivers of sustainable production in the automotive industry? What approaches, methodologies and tools have been used so far for measuring and supporting more sustainable vehicle?**

2. **Can LCSA be a supporting tool in the early design phase of vehicle components? Which are the challenges to make it fully applicable?**

3. **Which are the main trials related to lightweighting strategy? Which are the main design aspects influencing the lightweighting benefit from a sustainability perspective?**

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[4] http://product-social-impact-assessment.com/

In the framework of this overarching goals, the research would contribute to the LCSA advancements by providing insights in terms of: i) methodology progress; ii) data availability. Yet, LCSA growth relies on advancements of the single techniques which constitute it - LCA, LCC and S-LCA.

Figure 1 represents the scheme of the research contributions and it will be used to guide the results presentation in this thesis.

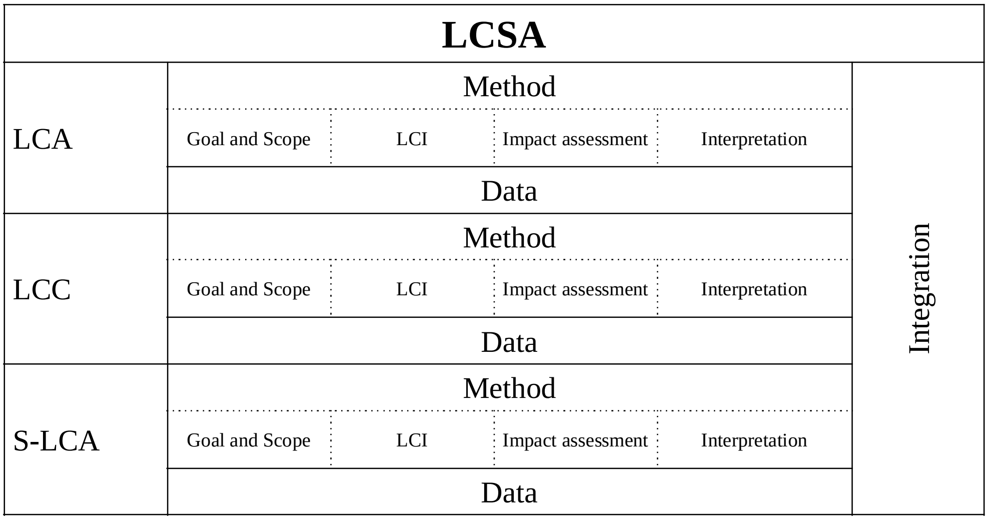

Figure 1 Scheme of research contributions to LCSA methodology

As far as LCSA concerned the main sub-questions are:

- What is the state-of-the-art of LCSA, in terms of knowledge, applications and needs, in the automotive sector?
- Which are the available methods to integrate LCA, LCC and S-LCA results?
- Can multi-criteria methods be the instrument for integrating results in a transparent and feasible way, avoiding impacts compensations?

Although LCA is a mature methodology and it is already spread in the automotive sector as a supporting tool in the design process, the following questions have been addressed to enhance its role in the LCSA framework:

- What is the state-of-the-art of data set concerning materials and manufacturing technologies in the lightweight panorama in terms of database and literature availability?
- Which are the environmental hotspot of lightweigthing? And which are the design parameters influencing the final result?
- Are there most important/relevant environmental impact categories for the automotive sector?

As far as the LCC methodology is concerned, the following sub-questions have been addressed:

- What is the state-of-the-art of LCC in the lightweighting design of automotive sector in terms of knowledge, applications and needs?
- Is it conventional or environmental LCC approach generally applied and how is it discussed? Are the critical methodological settings (i.e. perspective, cost categories) generally discussed in the economic analysis?
- Which are the most important cost categories in the lightweight design context? Which externalities need to be included?
- Which are the most important parameters, both technical and methodological, influencing the economics of lightweighting design solutions?

S-LCA is the last methodology developed, therefore many open issues exist in terms of methodological settings, and applications are required to better face such aspects, in addition to the theoretical developments. In this research project the following questions have been addressed:

- What are the main challenges to and drivers of social assessment production in the automotive industry?
- What is the state of the art of S-LCA methodology and its application in the automotive sector?
- How goal and scope can be defined in a social assessment?
- Which are the available social indicators?
- How social data can been collected? Which are the main obstacles for their gathering and treatment?

Overall, the purpose of this research is to evaluate benefit and criticism associated with LCSA use as a supporting tool to make decisions during the design process of vehicle components when lightweight strategy is applied. The method by which the research has been developed is described in the following chapter.

1.3. Structure of the thesis

The thesis is structured as follows. The introduction, describing the research framework and the research questions, and the method adopted for the research are described in *Chapter 1* and *Chapter 2,* respectively.

The LCA case studies are presented in *Chapter 3,* where outcomes and discussions regard impact assessment results, as well as data availability development concerning alternative materials and manufacturing technologies applied for component lightweighting purpose.

In Chapter 4 the most important LCC settings, among the ones stemmed from the literature review, are discussed, with the purpose to structure the LCC application for the assessment and comparison of lightweight solutions of vehicle components. A validating case study is also presented.

As far as the S-LCA is concerned, the starting point of the analysis is a critical review of S-LCA papers, which allowed to identify and evaluate the most important elements affecting the goal and scope and inventory phases of the S-LCA. Those elements are then structured into a conceptual map which is furthermore discussed in order to be targeted to the automotive sector (*Chapter 5*).

The integration of LCA, LCC and S-LCA results is discussed in *Chapter 6*. Among the different methods and approaches derived from literature, the Multi-Criteria Decision Analysis (MCDA) has been identified as a suitable approach. In fact, MCDA helps decision makers to choose the best option when a wide range of criteria has to be considered and compensation needs to be avoided. After a review of the most used and suited MCDA methods, the TOPSIS has been selected. This method develops ranking of alternatives assuming that the most preferred alternative should have the shortest distance from the positive ideal solution as well as the farthest distance from the negative ideal solution. Overall, a set of quantified social, economic and environmental sustainability indicators have been identified for the S-LCA, LCC and LCA respectively, and an online survey was proposed to prioritizing them according to the judgment of experts belonging to different sectors. The survey was mainly addressed to people belonging to the automotive sector, both as members of industry and as researchers in the sustainable transportation field, and people working in the sustainability and Life Cycle Assessment area. Next, results from the survey were analysed and furthermore treated by means of the intuitionistic fuzzy set method in order to avoid ambiguity and determine the weights of indicators which are needed for the TOPSIS method.

Results and discussions derived from the LCSA application to two real case studies – a part of the suspension system and a panel dashboard – are presented in *Chapter 7*. The two applications gave the opportunity to tackle with different methodological challenges, goal and scope settings, S-LCA data collection, S-LCA impact assessment method, and results integration, among others.

Finally, conclusions, limitations of the research and further investigation are drawn.

Additionally, the thesis includes Appendix sections, where the following additional information is provided: use stage modelling parameters (Annex A), full LCA results (Annex B); list of economic, environmental and social indicators selected and related weights (Annex C); Extended S-LCA results from case studies (Annex D).

1.4. Publications

The articles published during the research period are here listed, and the relation with the Chapters of this thesis is also expressed.

- Zanchi, L., Delogu, M., Ierides, M., Vasiliadis, H. (2016) Life Cycle Assessment and Life Cycle Costing as Supporting Tools for EVs Lightweight Design. In: Setchi, R., Howlett, R.J., Liu, Y., Theobald, P. (Eds.), Sustainable Design and Manufacturing 2016, Smart Innovation, Systems and Technologies. Springer International Publishing, pp. 335e348. ***(Chapter 3, Chapter 4)***;
- Delogu M, Zanchi L, Maltese S, Bonoli A, Pierini M (2016) Environmental and Economic Life Cycle Assessment of a lightweight solution for an automotive component: a comparison between talc-filled and hollow glass microspheres-reinforced

polymer composites. Journal of Cleaner Production 139 (2016) 548-560. http://dx.doi.org/10.1016/j.jclepro.2016.08.079 ***(Chapter 4, Chapter 7)***;

- Zanchi, L., Delogu, M., Zamagni, A., Pierini, M. (2016) Analysis of the main elements affecting social LCA applications: challenges for the automotive sector. Int. J. Life Cycle Assess. http://dx.doi.org/10.1007/s11367-016-1176-8. ***(Chapter 5)***;
- Zanchi, L., Delogu, M., Zamagni, A., Pierini, M. (2015) Social issues in the automotive sector: review of existing approaches and the social SLCA application scene. 7th International Conference on Life Cycle Management, 30th August – 2nd September 2015, Bordeaux, France ***(Chapter 5)***;
- Delogu, M., Zanchi, L., Pallacci, T., Pierini M. (2016) Analisi comparativa di sostenibilità ambientale a supporto della progettazione di un componente automobilistico alleggerito. AIAS – Associazione italiana per l'analisi delle sollecitazioni 45° convegno nazionale, 7-10 settembre 2016 – Università Degli Studi Di Trieste ***(Chapter 3)***;
- Delogu, M., Maltese, S., Del Pero F., Zanchi, L., Pierini, M. Case study of lightweight design solution for an automotive powertrain component combined with Life Cycle Impact Assessment (submitted to Materials and Design) ***(Chapter 3)***;
- Dattilo, C.A., Zanchi, L., Del Pero, F., Delogu M. Sustainable Design: an Integrated Approach for Lightweighting Components in the Automotive Sector (submitted to SDM 2017) ***(Chapter 3, Chapter 4, Chapter 6)***;
- Maltese, S., Zanchi, L., Delogu, M., Bonoli, A. Application of Design for Environment principles combined with LCA method on product process development to enhance the sustainability of automotive sector: a case study application of crossmember (submitted to Journal of Industrial Ecology) ***(Chapter 3)***.

2. Method

The LCSA methodology has been recently proposed, therefore there is a need of reviewing and discussing methodological aspects besides investigating its potentials by means of case studies.

Overall this research has been developed following two pathways: the first dedicated to the methodological trials which emerged from the state of the art of LCSA and related techniques (LCA, LCC and S-LCA); the second focused on the data availability and data gathering as a relevant aspect to foster the methodology progress and spread.

The general method has involved an initial state of the art phase, during which the open methodological aspects are identified and discussed; some of those elements are examined in more details also by means of case studies. The main strong points of these studies are the possibility of collecting primary data and modelling several design solutions for different kinds of vehicle systems, as well as the possibility of presenting and interpreting results with companies directly involved in the component production. Additionally, activities dedicated to stakeholder engagement have been proposed (on site visit, online survey).

The critical review has been carried out, which covers 135 publications, both scientific and grey literature in the field of LCA, LCC, S-LCA and LCSA in the automotive sector over a time span of 10 years, from 2006 to 2016.

In the automotive sector, as in all the sectors where innovation and sustainability represent competition elements, published practices are not necessarily the same as the internal practice of OEMs. For this reason, this research refers only to studies and procedures publically available.

Scopus, sciencedirect, and googlescholar were used as search engines, with the following keywords: life cycle assessment AND lightweighting, life cycle assessment AND composite, life cycle costing AND automotive, life cycle costing AND lightweighting, life cycle costing AND composite, life cycle costing, total cost of ownership, life cycle cost AND automotive, life cycle cost AND lightweighting, social LCA, social life cycle assessment, life cycle sustainability assessment, life cycle sustainability, social sustainability, social LCA AND automotive, social sustainability AND automotive, sustainability AND automotive.

Works on LCA applied in the lightweight design, resulted in 25 articles, have been reviewed with the aim of identifying the most important advantages/disadvantages caused by the substitution of traditional materials with lighter ones (i.e. aluminium, carbon fibres- and glass fibres- reinforced plastic) and analysed so far. The current available database, in particular GaBi, have been reviewed to identify available dataset concerning materials production (polymers, fibres, metals), technologies dedicated to metals and composites manufacturing, and processes for the EOL treatment of vehicles/components and materials recycling (i.e. shredding, VW-Sicon). A limit coverage about some specific materials and processes was found, therefore a desk research has been accomplished with the aim of collecting data concerning energy and materials consumption, and scraps production during composite processing and related manufacturing technologies (i.e. RTM, injection moulding). In addition, activities developed within the framework of ENLIGHT project and collaborations with Magneti Marelli ® and another automotive manufacturer gave the opportunity to collect primary data about innovative materials (i.e. Textreme ® reinforcement) and new manufacturing technologies (i.e. Advanced Sheet Compression Moulding) involved in real case studies where a lightweight design is compared with a reference one. To do that, specific templates have been developed and submitted to partners, to collect data (i.e. electricity consumption, scraps production and reuse).

The review of LCC articles compels (20) works which respond to the aforementioned keywords and that were not further selected. The review has been guided by the need of identifying the awareness level and spread of LCC application in the automotive sector, lightweight design in particular; how and if the methodological elements described by the Code of Practice (Swarr et al. 2011) and Hunkeler et al. (2008) (i.e. assessment type, perspective, discounting, externalities) are followed and reasoned are also reviewed. In particular, for every element the review would find out if sector reasoning have been proposed or if studies rely on subjectivity. Real case study on LCC gave the opportunity to sum up all the reasoning about FU, perspective, cost categories, discounting, etc. as well as providing an example of a detailed data collection in collaboration with OEM.

As far as S-LCA concerned, the review includes 89 papers both stand-alone S-LCAs and those carried out within a more comprehensive LCSA since, in the author opinion, different but interrelated and mutual helpful perspectives could be observed. For the automotive sector the review has included also the corporate-related documents, selected among the best-selling car manufacturers in Europe in the last years (ACEA 2015a). The reviewed papers have been analysed and discussed in terms of key elements affecting the goal and scope and inventory phases of the S-LCA case studies according to the best knowledge of the author and to literature findings (Petti et al. 2014). Those elements have then been organized into a conceptual map where all the methodological and practical issues have been sequentially placed by taking into account how they could affect the goal and scope and inventory phase of the S-LCA methodology. This sequence is intended to support S-LCA applications by means of highlighting and structuring key decision points the practitioner has to cope with. The aim of the conceptual map is not to solve open methodological issues but to push practitioners in critically facing all of them and therefore contribute to the enhancement of the S-LCA. The conceptual map is then discussed by means of the case studies of the automotive sector, both S-LCA applications and sustainability reports. The S-LCA studies provided support to better understand the key methodological options and possible solutions for each node of the conceptual map (i.e., functional unit, system boundaries), whereas the corporate-related documents supported the identification, selection, and measurement of the social issues taken into account by the companies of the sector; the stakeholders involved and the engagement practices generally applied have also been considered. Among the several initiatives, the Roundtable for Product Social Metrics has been selected as guideline; in particular the quantitative approach has been studied and applied for the S-LCA part within LCSA studies.

Review of LCSA studies (28) was mainly focused on methodological setting able to guarantee appropriateness of goal and scope definition within a sustainability framework, and approaches and mathematical methods to integrate results. The Multi-Criteria Decision

Analysis (MCDA) has been identified as a suitable approach to integrate LCA, LCC and S-LCA results; in particular the TOPSIS method has been chosen. The applicability of such approach, in relation to others, and its presence in the sector are the main reasons of such choice. On-line survey for prioritisation in TOPSIS was proposed to prioritize a certain number of environmental, economic and social criteria. The survey was mainly addressed to people belonging to the automotive sector, both as members of industry and as researchers in the sustainable transportation field, and people working in the sustainability and Life Cycle Assessment area.

Case studies, concerning suspension system and dashboard design, gave the opportunity to develop a detailed LCSA and discussing many aspects. First, the goal and scope phase is developed taking into account peculiarities of the social assessment, according to the conceptual map; then the inventory phase has been developed for the environmental, economic and social parts including primary data gathering. For the social part, the quantitative questionnaire has been used and feasibility of its indicators has been tested, moreover also PSILCA database have been examined. Data collection has been carried out by means of specific template and on site meeting at the manufacturing site with the aim of supporting companies and enhance managers/designers engagement.

3. Life Cycle Assessment: data and case studies for ICE and EVs

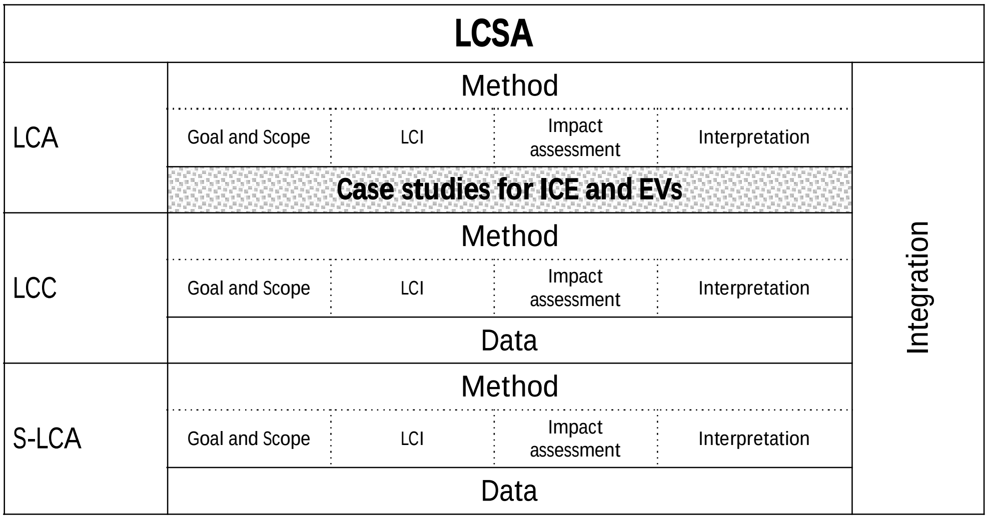

Figure 2 Scheme of research contributions to LCSA methodology: LCA data and case studies for ICE and EVs

The environmental consequences of lightweight design are particularly discussed in the current literature, however the continuous advancement in terms of materials and related manufacturing technologies provides additional elements to be examined.

Data availability is generally claimed to be an important researching filed, in fact the current database do not completely cover the materials and processing involved in the production stage of vehicle, as well as in the EOL treatments.

Moreover the benefits of weight reduction via material substitution are not generally guaranteed since they strongly vary depending on design conditions and are particularly sensitive to some methodological settings (e.g. life span distance, use stage modelling approach). Beside the urgent improvements in terms of CO_2 emissions, other environmental effects need to be taken into account in order to avoid burden shifting along environmental compartments.

This research aims at providing contributions in terms of data collection for the eco-profile modelling of a certain number of novel materials and manufacturing technologies;

moreover, it examines the environmental life-cycle implications under specific design conditions. For example, lightweighting is seen as an opportunity to reduce fuel consumption and consequently emissions during the use stage of internal combustion engine (ICE) vehicles. However, the electric vehicles (EVs), which are seen as a promising solution for the decarbonization of transports, are also involved in lightweighting processes targeted to improve EVs performances in terms of drive distances and battery size containment (Bein et al. 2016).

During the present research a set of lightweighting case studies were carried out. They are all real case studies developed in collaboration with OEMs and regard the lightweighting of several components of both ICE and EVs. They were selected according to the following criteria: i) lightweight potential; ii) comparative assessment where a reference design solution is compared with a composite-based or multi-material design; iii) use of innovative materials and related technologies. In this sense they could enable an in-depth analysis of environmental issues related to lightweight solutions and which needs to be conveyed in the Life Cycle Sustainability Assessment framework (Figure 2).

The main outcomes regard: (1) a literature review of works on LCA applied in the lightweight design (cfr. § 3.1), (2) intensive data collection, involving both primary data and secondary data, regarding materials and manufacturing technologies of a number of case studies (cfr. § 3.2, 3.3), (3) analysis of effective benefit and risk stemmed from innovative materials (composite) application when component lightweighting is developed in internal combustion engine and electric vehicles (cfr. § 3.4), (4) discussion about additional environmental impact categories, beyond the Global Warming Potential one (cfr. § 3.4.), (5) analysis of the technical elements influencing the final environmental performance by means of additional indicators relating LCA results with design aspects (cfr. § 3.4).

3.1. LCA in the automotive lightweight design

Life Cycle Assessment (LCA) is already used by several companies in the automotive field, as demonstrated by the high amount of technical reports by car manufacturers (Renault 2011; Volkswagen AG 2012; Mercedes-Benz 2013) and scientific publications (Finkbeiner and Hoffmann 2006; Hawkins et al. 2013; Koffler 2013). Several studies have explored the potential for environmental impact reduction through lightweighting, in that LCA is applied both at vehicle and component level.

Recent studies have attempted to analyse and review LCA lightweighting case studies, trying to give an overview about weaknesses and strengths of material substitution. Overall, the use of lightweight materials could lead to fuel saving and use stage emissions abatement, nevertheless it is often responsible for increase in the production stage impact, particularly materials processing, thus counterbalancing the expected benefit during use (Kelly et al., 2015; Kim and Wallington, 2013). The life cycle energy consumption in a steel-based scenario is generally dominated by the use stage, counting for 66-97%, and materials production ranges between 3 and 20%; whereas in a general lightweight scenario the materials production increases noticeably up to 3-55% (Kim and Wallington 2013). Such distribution changes considerably in an electric vehicle life cycle where the use stage impact, more properly the Well-To-Tank[5] stage, could contribute for lower that 50% (depending on

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[5] Well-To-Tank: the steps required to produce and distribute a fuel (starting from the primary energy resource), including vehicle refuelling

electricity grid mix) (Girardi et al. 2015). As a consequence, with increase of production stage and reduction of use stage as in EVs there might be new insights, however very few studies have been published so far about this topic.

Overall, this sensitive balance between use stage benefits and production stage weakness is influenced by many aspects. Kelly et al. (2015) discussed material substitution ratio and material pairs for different vehicle parts; steel is generally proved to provide a large potential for weight reduction and when it is replaced by high strength steel, advanced high strength steel and cast aluminium allow also GHG emission reduction since from the production stage. On the other hand, wrought aluminium, carbon-fibre reinforced plastic (CFRP) and magnesium yield relevant mass reduction but at the cost of GHG emissions increase during material processing. When the analysis is extended to the life-cycle GHG emission, thus including the emission reduction during the use stage due to mass reduction, the fuel reduction value (FRV) and life distance were found to influence a lot the final results. Indeed, increasing life distance produces higher GHG emissions reduction over the reference solution; a wide range of vehicle life span values are used in the literature studies, ranging between 96 000 and 260 000 km (Kim and Wallington 2013), while 150 000 km, 200 000 km, and 250 000 km are identified as the most appropriate within a typical calendar lifespans of 10 to 13 years (Del Duce et al. 2013).

Moreover, the FRV value affects the breakeven driving distance in a considerable way especially when steel is replaced by wrought aluminium, magnesium of CFRP in a high substitution ratio (the lower FRV value, the higher breakeven driving distance) (Kelly et al. 2015). Despite there have been many LCA studies on the benefits of vehicle lightweighting, the wide variety of assumptions used does not allow compare the results from the studies; Kim and Wallington (2013) investigated the influencing level of some methodological settings (e.g. life distance, recycling assumptions, secondary weight saving) and analysed LCA results after an harmonization process. It confirmed that using aluminium, glass-fibre reinforced plastic, and high strength steel to replace conventional steel yields to significant energy and GHG emissions reduction. In conclusion, whether lightweighting reduces life cycle impacts was found to depend on methodological assumptions but also on data quality; as a consequence, careful data handling is necessary to obtain clear and reliable outcomes. In this sense further investigations would regard materials processes data, especially new materials like magnesium and carbon-fibre reinforced plastic (Kim and Wallington 2013).

Table 1 reports those reviewed studies (18) where specific LCA case studies are presented to evaluate and compare materials for components mass reduction. For each paper, the following aspects have been reported: component name, compared materials, impact categories and data quality.

Table 1 Review LCA case studies of lightweighting (D=database; L=literature; P=primary)

Source	Component name	Material pairs	Impact categories	Data quality
(Alves et al. 2010)	Front bonnet	Fibres vs. Fibres	Not specified	D
(Andriankaja et al. 2009)	Dashboard, seat	Metal vs. Composite	GWP, ADP, EP, ODP, POCP, AP	D
(Das 2011)	Section floor	Metal vs. Composite	PED, GHG, GWP	L
(Dhingra and Das 2014)	Engine	Metal vs. Composite	CED, GWP	L
(Duflou et al. 2009)	BiW	Metal vs. Composite	GWP, ADP, EP, ODP, POCP, AP	L
(Kelly et al. 2015)	Several parts belonging to different vehicle systems	Metal vs. Composite	GHG	L
(Koffler 2013)	Assist step, front end bolster	Metal vs. Composite	PED, GWP, AP	D, L
(Luz et al. 2010)	Not specified	Fibres vs. Fibres Composite vs. Composite	ADP, AP, EP, GWP, ODP, POCP	D, L
(Mayyas et al. 2012b)	BiW	Metal vs. Composite	GWP, PED	L
(Park et al. 2013)	Front side panels	Metal vs. Composite	Not specified	Not specified
(Rajendran et al. 2012)	Generic panel	Fibres vs. Fibres	GWP, ADP, EP, ODP, POCP, AP, HTP	Not specified
(Raugei et al. 2015)	BiW and chassis parts	Metal vs. Composite	HTP, GWP, AP, CED	Not specified
(Schuh et al. 2013)	BiW	Metal vs. Composite	GWP, CED, ODP	D
(Subic et al. 2010)	Passenger seat	Metal vs. Composite	ADP, AP, EP, GWP, ODP, POCP	D, L
(Tharumarajah and Koltun 2007)	Engine block	Metal vs. Metal	GWP	D, L, P
(Tharumarajah and Koltun 2010)	Front Instrument panel	Metal vs. Composite	GHG	L
(Vinodh and Jayakrishna 2011)	Steering system parts	Metal vs. Metal	CF, EP, AP, PED	D
(Witik et al. 2011)	Bulkhead	Metal vs. Composite	GWP	D

As it can be seen, some studies regard vehicle parts (e.g. engine block, passenger seat) while others concern system-level analysis (e.g. Body-in-White). The substitution of traditional metals (steel) with composites is one of the most studied issues, few studies compared alternative composites. Nevertheless, despite the high number of literature in this topic, we are still far from having a clear and homogeneous overview of advantages associated to such design solution. Moreover, the objectives suggested by the current European directives (i.e. CO_2 reduction during use stage)(EC 2000; EC 2009) should be integrated with a life cycle perspective to build a comprehensive strategy to develop more environment-friendly vehicles and to avoid burden shifting from one stage to another (Witik et al. 2011).

The review of LCA applications (Table 1) stresses that in most of the case data are retrieved from database or literature, and few of them rely on primary data.

The reviewed studies only regard lightweighting of ICE vehicle, while lightweighting for other vehicle propulsion systems, especially at component level, are not considered by none of the LCA studies, to the best knowledge of the author.

Fuel consumption, GHG emissions and life-cycle energy demand are the most studied environmental indicators, as emerged also from the reviewed studies in Table 1. This can be ascribed to the current directives, nevertheless they are not the only burdens generated throughout a vehicles life cycle, so other environmental indicators should be included (Hawkins et al. 2013; Raugei et al. 2015). This is particularly important when the production and the EOL stages are addressed. Use of novel materials may have other types of impact; thus the addition of indicators for resource depletion and toxicity could be important (Raugei et al. 2015).

The recent methodological developments in LCA go in the direction of sector-specific and context-specific approaches (Del Duce et al. 2013) as opportunity to strength its decision support role in the day-by-day management. Defining a set of environmental indicators targeted to the given sector is generally debated, in particular the association of indicators used in LCA with other environmental engineering metrics currently used in the automotive sector is discussed by many authors (Andriankaja et al. 2009; Renault 2011; Andriankaja et al. 2015).

Overall, the impact categories which should be evaluated by default for relevance to the study are: Climate change, (Stratospheric) Ozone depletion, Human toxicity, Respiratory inorganics, Ionizing radiation, (Ground-level) Photochemical ozone formation, Acidification (land and water), Eutrophication (land and water), Ecotoxicity, Land use, Resource depletion (metals, minerals, fossil, nuclear and renewable energy sources, water) (Del Duce et al. 2013). In some case, a selection of environmental impact categories is carried according to specific criteria: relevance (contributions known and supposed of automotive product), feasibility, consistency (diversity of ecosystems, local biodiversity and global resources depletion) and viability. Global warming, abiotic depletion and energy demand gained the highest score, followed by water eutrophication, photochemical pollution and acidification. Aquatic Ecotoxicity, biodiversity and Land Use Change were seen at the lowest level (Renault 2011).

It can be argued that the environmental indicators selection has been guided also by the perceived relevance of the life cycle stage, so pollutants air emissions (e.g. NO_X, CO, PPM) and GWP are so applied since mainly related to the use stage. Nevertheless, other indicators shall be selected to evaluate raw materials and EOL stages burdens. Resource depletion is claimed to be a very important issue and several methods exist, however none of them can be elected as then most appropriate for the moment. The Abiotic Depletion

Potential, from the CML method, is a widespread impact category, moreover it is recommended in the ILCD framework (EC-JRC 2011) since addresses the scarcity of the resource. Yet its robustness is discussed and specific initiatives currently exist at European level to improve and integrate this category (Sala et al. 2016). Other metrics can be found in literature, rate of renewable materials and rate of recycled material, among others (Andriankaja et al. 2009). The toxicity – human and ecological – is another discussed issue; beside the availability of clear and robust indicators, very few works include this aspects in the lightweighting assessment (Raugei et al. 2015; Girardi et al. 2015). However, it can be argued that such topic will become more and more influent since electric elements (e.g. batteries) will increase and treatment of other toxic materials (oil, batteries, heavy metals) will receive more attention in the LCA studies (Martinuzzi et al. 2011). Direct water consumptions of materials, vehicle and fuels production and the impact due to such withdrawals are assessed (Warsen et al. 2011). Beside the inherent uncertainties from impact assessment methods and generic datasets for this analysis, the freshwater consumption of three specific vehicle models along their product life cycles has been evaluated (Warsen et al. 2011). A wide range of water consumption values are reported (at inventory level), overall it is claimed that the consumption in material production is the highest (steel, aluminium and rubber) while the EOL processes represent the lowest contribution (Bras et al. 2012). Indeed, we are still far from having a clear understanding about this issue which certainly would require further investigations.

The EOL stage of vehicles also require the integration of LCA and other metrics. Many studies dealing with EOL -Vehicles (ELVs) issues in road transportation exist in the literature (Schmidt et al. 2004; Giannouli et al. 2007; Go et al. 2012; Berzi et al. 2016). Overall, two important aspects need to be detected in the analysis of the EOL stage: i) environmental burdens produced by the EOL processes; ii) recyclability and recoverability of the component.

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

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

All the technologies involved in the EOL stage are responsible for impacts, mainly due to energy consumption and processes efficiency, which necessary need to be calculated and compared with the expected benefit from the material recycling and energy recovery; for this reason, beside recyclability and recoverability analysis, it is important to evaluate the EOL impacts according to the environmental indicators proposed in the LCA framework (GHK, Bio Intelligence Service 2006; Ciacci et al. 2010; Tian and Chen 2014) (GHK, Bio Intelligence Service, 2006; Ciacci et al., 2010).

All these works suggest that many aspects contribute to the conclusion that a *"simple clear-cut answer in terms of 'which strategy is best' may actually not exist"* (Raugei et al. 2015). The most important ones, retrieved by the reviewed studies, are: the wide range of materials and their continuous advancements also in terms of manufacturing technologies; the high number of data to be handled and their quality and availability; the wide variety of assumptions; the different environmental indicators. The following studies will be described trying to cover all these elements in order to be transparent in all the assumptions and providing a detailed data collection.

3.2. Case studies description

In this paragraphs a brief description of each case study is provided, references to the full analysis are also given.

All the studies were performed on the bases of LCA methodology, thus defining a coherent functional unit suitable for the comparison between the standard solution and the innovative/s one/s. The following assumptions are common to all the cases:

- The reference (Ref.) and lightweight (Light) solutions guarantee the same performances in terms of functionality, safety and mechanical behaviour;
- The Functional Unit is properly defined, to enhance comparison, as the given component providing the specific functionality (e.g. the distribution of 105 kg/h air intake flow to the individual cylinders of a 1200-cc naturally aspirated internal combustion engine) during a life-distance of 150,000 km for 10 years;
- Use stage modelling assuming 150,000 km of life distance and an analytic model based on the fuel reduction value approach (Koffler and Rohde-Brandenburger 2009), more details are provided in Annex A;
- Impact assessment by means of CML2001 method;
- The EOL stage is modelled according to one or more scenarios, taking into account the peculiarities of the component (materials and accessibility). It is discussed in more details for each case study;
- Data on processing and materials are derived from primary data, when direct measurements could be provided by material suppliers and manufacturers, or secondary data, in particular GaBi database or literature. Further details about data sources are described in § 3.3.

The components are described in the following according to reference vehicle system: powertrain, Body-in-White, Chassis and suspension, Closure and Interior. Such case studies mainly represent structural parts of a vehicle, indeed electrical components (battery, lighting, etc.) are not included in this work.

3.2.1. Powertrain

Air intake

The environmental impacts of an air intake produced by Magneti Marelli was carried out. The primary function of this component is to ensure 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.

It consists of a volume of thermoplastic material with high thermal and mechanical resistance; in this case a traditional design, based on polyamide reinforced with GF, is compared with a lighter solution made with polypropylene reinforced with GF (Table 2). Moreover, the two solutions are compared also by considering alternative scenarios in terms of scraps recycling during the manufacturing stage and the elimination of brass inserts. More details about this study is reported in (Delogu et al. 2015). The change in the material was found to produce the most important change in the potential impacts (Delogu et al. 2015), so in this paragraph only the comparison between materials is provided.

The difference in mass is primarily due to material change in the central body, lower cover and upper cover, whereas all the other sub-parts, corresponding to a mass contribution lower than 5%, remain the same (Delogu et al. 2015).

Table 2 Data on mass, materials and technologies for the air intake solutions

	Mass [kg]	Materials	Technologies
Light solution			
			
Central Body	0.870	PP-GF35	Injection moulding and welding
Lower Cover	0.269	PP-GF35	Injection moulding and welding
Upper Cover	0.374	PP-GF35	Injection moulding and welding
Total	1.51 (-15%)		
Ref. solution			
Central Body	1.024	PA6-GF30	Injection moulding and welding
Lower Cover	0.316	PA6-GF30	Injection moulding and welding
Upper Cover	0.440	PA6-GF30	Injection moulding and welding
Total	1.78		

For the modelling of the use stage (Annex A), a reference vehicle with the technical characteristics reported in Table 3 was assumed. Accessibility is a key aspect for the removal of the component from the engine system, in fact the dismantling time and component mass are crucial factors in order to determine whether the air intake should be removed or not. In this case it was assumed that the component remains on the vehicle, in accordance also with the on-field investigation of ELV treatment in the context of Italian craft-type authorized treatment facilities (Berzi et al. 2013). Therefore, the EOL stage included energy consumption for shredding process and impacts from materials landfilling.

Table 3 Technical data referring to vehicle model equipped by the air intake

Data	**Unit**	**Quantity**
Vehicle model:	-	naturally aspirated gasoline 1600 cm^3, 74 kW
Vehicle mass:	kg	1280
Emission stage (e.g. EURO5):	-	EURO5
Vehicle fuel consumption (mixed urban-extra):	l/100km	6.4
CO_2 emissions:	g/km	164
FRV value:	l/100 km×100 kg	0.15

Throttle body

The environmental impacts of a throttle body produced by Magneti Marelli was carried out. The throttle body is an electromechanical component whose function is to regulate engine inlet air flow basing on pressure exerted by driver on accelerator pedal, it is connected to the engine intake manifold (at output) and it is constituted by a valve plate that controls the inlet flow rate by regulating the net air passage. The component is characterized by high miniaturization and constituted by 18 parts; the main part of the throttle body is the housing which corresponds to 51% of the reference total mass. The mass reduction would be reached thanks to two main actions: material substitution for the housing and simplification of other parts thanks to the adoption of different design solutions; nevertheless the first aspect was found to affect more the total mass so further results will be discussed regarding the effect of material substitution. More details are reported in (Magneti Marelli 2015).

In particular a reference design, based on Aluminium (roughly 90% secondary Aluminium), is compared with a lighter solution made with polyethylene reinforced with GF; materials, masses and technologies for the two different solution are reported in Table 4.

Table 4 Data on mass, materials and technologies for the throttle body solutions

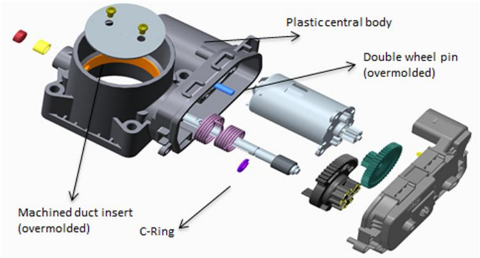
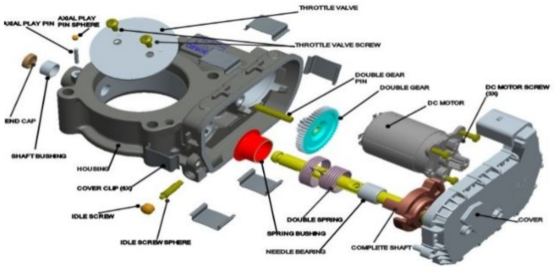
	Mass [kg]	**Materials**	**Technologies**
Light solution			
			
Housing	0.25	PET+GF50	Extrusion + Injection Moulding
Other parts	0.42		
Total	0.67 (-22%)		
Ref. solution			
			
Housing	0.44	Aluminium (AlSi13Fe)	Pressure Die Casting
Other parts	0.42		
Total	0.86		

Table 5 shows technical data referring to car model equipped by the throttle body; those data are used for the use stage modelling (Annex A).

Table 5 Technical data referring to car model equipped by the throttle body

Data	**Unit**	**Quantity**
Vehicle model:	-	Audi RS6 4.0 TFSI
Vehicle mass:	kg	1935
Emission stage (e.g. EURO5):	-	EURO5
Vehicle fuel consumption (mixed urban-extra):	l/100km	7.5
CO_2 emissions:	g/km	229
FRV value:	l/100 km×100 kg	0.12

For both solutions the EOL scenario considers that the throttle body remains on the vehicle, thereafter it is led to the shredding and milling processes, contributing to the production of the so-called fluff or Automotive Shredder Residue (ASR). After the shredding, an ASR separation process is assumed, which separates pure ferrous materials and non-ferromagnetic materials from a mixture of different materials (i.e. plastics, fibres, glass, elastomers). The first flow is intended to be recycled whereas the second to be landfilled. Data used for the modelling are reported in Table 6.

Table 6 Data inventory EOL stage throttle body

Data	Unit	Value	Source
Electricity consumption for ferrous metal treatment	kWh/ton	40	Primary data
Electricity consumption for non-ferrous metal treatment	kWh/ton	25	Primary data
Electricity consumption for ASR treatment	kWh/ton	7	Primary data
Credit recycling of steel (sorted automotive castings scrap credit)	%	47	GaBi
Credit recycling of aluminium (auto fragments scrap credit)	%	42	GaBi

3.2.2. Body-in-White

Three different components belonging to the Body-in-White (BiW) system were analysed, two of them are mounted over an EV while one is assembled to an ICE vehicle.

Front module

Front module of a vehicle is the aggregate of components located in its front part which carry out many functions (esthetical, structural, aero dynamical, engine cooling, safety) and which are preassembled as subassembly ready to be installed into the vehicle. In this work, the front module consists of four sub-modules: 1) crash management system, 2) front longitudinal member; 3) strut dome and wheel housing; 4) front corner node (Figure 3).

A reference solution, based on steel and aluminium, is compared with a lightweight one, based on multi-material design where aluminium and composite are applied. The alternative solution was developed in the framework of ENLIGHT project.

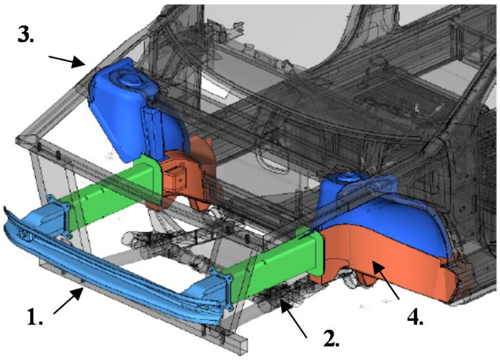


Figure 3 Front module components

Each sub-module comprises different mono-material parts listed in Table 7 and Table 8; materials and manufacturing technologies of reference and lightweight solutions are reported along with the mass reduction achieved for each sub-module (Table 7 and Table 8). More details are described in the project deliverables (D7.2).

Table 7 Data on mass, materials and technologies for all the subsystems of front module (Lightweight solution)

Light solution	**Mass [kg]**	**Materials**	**Technologies**
1. Crash management system			
Crash box	0.88	Aluminium	Extrusion and Forming
Deflection plate	0.45	Aluminium	Punching and drilling
Towing adapter	0.22	Aluminium	-
Bumper cross member 1	1.71	High Strength Steel	Roll forming
Bumper cross member 2	0.29	PA410-CF60	Thermoforming
Total	3.55 (-23%)		
2. Front longitudinal member			
Aluminium profile	1.73	Aluminium	Extrusion
CFRP tube	1.00	PA410-CF60	Airborne winding
Deflection plate front	0.56	Aluminium	Deep drawing and drilling
Deflection plate rear	1.22	Aluminium	Deep drawing and drilling
Total	4.52 (-9%)		
3. Strut dome and wheel housing			
Strut dome	3.11	PA410-CF60	Thermoforming
Top reinforcement	2.74	Steel	Deep drawing
Side reinforcement	0.40	PA410-CF60	Thermoforming
Connection element upper	0.16	Aluminium	Deep drawing
Connection Element lower	0.12	Aluminium	Deep drawing
Total	6.54 (-30%)		
4. Front corner node			
Corner node up.	3.09	PA410-CF60	Thermoforming
Corner node lower	2.43	PA410-CF60	Thermoforming
Aluminium reinforcements front	1.72	Aluminium	Bending
Supp. bracket 1	0.61	Steel	Deep drawing
Supp. bracket 2	1.06	Steel	Deep drawing
Supp. bracket 3	0.39	Steel	Deep drawing
Total	8.69 (-54%)		

Table 8 Data on mass, materials and technologies for all the subsystems of front module (Reference solution)

Reference solution	**Mass [kg]**	**Materials**	**Technologies**
1. Crash management system			
Crash box	0.88	Aluminium	Stamping
Deflection plate	0.45	Aluminium	Rolling
Towing adapter	0.22	Aluminium	Rolling
Bumper cross member 1	3.07	Steel	Stamping and bending
Total	4.62		
2. Front longitudinal member			
External profile	2.12	Aluminium	Rolling
Deflection plate front	1.48	Aluminium	Deep drawing
Deflection plate rear	0.56	Aluminium	Deep drawing
Total	4.16		
3. Strut dome and wheel housing			
Strut dome	3.44	Steel	Deep drawing
Top reinforcement	3.27	Steel	Deep drawing
Wheel housing	1.74	Steel	Deep drawing
Side reinforcement	0.56	Steel	Deep drawing
Connection element upper	0.14	Steel	Deep drawing
Connection Element lower	0.11	Steel	Deep drawing
Total	9.27		
4. Front corner node			
Corner node upper	8.39	Steel	Deep drawing
Corner node lower	7.76	Steel	Deep drawing
Reinforcement front	0.87	Steel	Deep drawing
Supp. bracket 1	0.61	Steel	Deep drawing
Supp. bracket 2	1.06	Steel	Deep drawing
Supp. bracket 3	0.40	Steel	Deep drawing
Total	19.08		

The module is mounted over an electric vehicle, therefore the use stage modelling is developed according to the approach described in Annex A; the analysis EOL scenarios is particular important since the potential critical aspects linked to the substitution of traditional materials with composites, need to be addressed. In this sense, two different scenarios were selected: a “current” scenario, based on shredding and post-shredding treatments; a “future” scenario where shredding is substituted by dismantling, whenever this is found feasible, and advanced post-shredding technologies are assumed. In the first scenario metals separation is followed by energy recovery from non-metallic flow; whereas in the second scenario also plastic/composite are supposed to be recycled. Data used for the EOL modelling are reported in Table 9.

Table 9 Energy consumption values of EOL processes

Process	Unit	Quantity	Source
Depollution (battery, oil, fluids, …)	MJ/kg	0.015	(ENLIGHT D7.2 2016)
Dismantling (tyres, bumpers, glass, ...)	MJ/kg	0.07	
Shredding (ferrous and no ferrous metals)	MJ/kg	0.18	
Post-shredding technologies (based on SiCon technology)	MJ/kg $_{\text{ASR}}$	0.12	
Pyrolysis	KJ/kg	10	(Das 2011)
Credit recycling of steel (aluminium auto wheels scrap credit)	%	47	GaBi
Credit recycling of aluminum (auto fragments scrap credit) (Current scenario)	%	42	GaBi
Credit recycling of aluminum (aluminium auto wheels scrap credit) (Future scenario)	%	70	GaBi
Credit recycling of carbon fibers (Future scenario)	%	50	(ENLIGHT D7.2 2016)

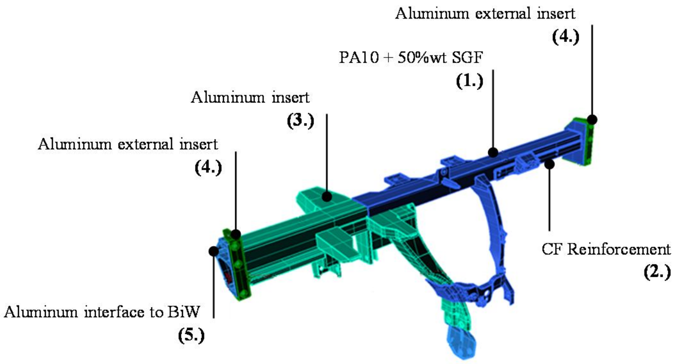
Cross dashboard beam

Cross dashboard beam is a complex parts of a vehicle, which make a decisive contribution to the stability and safety of every vehicle in which they are used, in fact it plays two main functions, first structural support for instrument panel subsystems and components, second structural support to body during crash (Figure 4).

Figure 4 Location of Cross Dashboard Beam in passenger vehicle

The lightweight solution, developed within the ENILGHT project, has been analysed in its main five parts, and it is compared with a reference solution made with steel (Table 10).

Table 10 Data on mass, materials and technologies for the cross dashboard beam solutions (ENLIGHT D7.4 2016)

	Mass [kg]	**Materials**	**Technologies**
Light solution			
			
1. Cross Car Beam	1.3	PA410-SGF50	Injection moulding
2. CF Reinforcement	0.4	PA410-CF WT	Thermoforming
3. Steering column Insert	3.1	Aluminium	Casting
4. External inserts	0.4	Aluminium	Casting
5. Interface to BiW	0.5	Aluminium	Extrusion
Total	5.7 (- 40 %)		
Ref. solution			
Steel part		---	Moulding
Total	10		

The cross dashboard beam is mounted over an electric vehicle, therefore the use stage modelling is developed according to the approach described in Annex A. The two EOL scenarios are: a “current” scenario, based on shredding and post-shredding treatments; a “future” scenario where shredding is followed by advanced post-shredding technologies; indeed dismantling was not considered a valid option due to the place of the cross dashboard beam which would require too labour intensive process. Data used for the EOL modelling are reported in Table 9.

Pedal box support

The environmental impacts of a pedal box produced by Magneti Marelli ® was carried out. The Pedal Box is located between the accelerator pedal sensor and the control module and works by capturing the accelerator pedal signal and transforms it. It is constituted by a series of components including the pedal support, whose contribution on total pedal weight is around 25%. The main function of the Pedal box support is to fix the three pedals to the body. In particular a traditional design, based on polypropylene matrix filled with 30% of glass fibres, is compared with a lighter solution made with polypropylene matrix filled with 40% of natural fibres (NF) (Table 11). These natural fibres are wood made (Woodforce[6]) and represents an innovative material since are compatible with all existing extrusion equipment, with global and large-scale industrial operations. Production stage of these fibres has been analysed by the reference Company which provides the impacts values (SONAE INDUSTRIA 2015).

Table 11 Data on mass, materials and technologies for the pedal box solutions (Magneti Marelli 2016a)

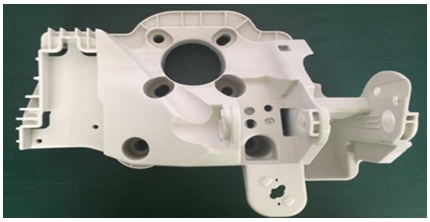
	Mass [kg]	Materials	Technologies
Light solution			
			
Total	0.79 (-9%)	PP-NF40	Injection Moulding
Ref. solution			
			
Total	0.87	PP-GF30	Injection Moulding

Table 12 shows technical data referring to vehicle model equipped by the pedal box; those data are used for the use stage modelling (Annex A).

For both solutions the EOL scenario considers that the pedal box support remains on the vehicle, thereafter it is led to the shredding and milling processes, contributing to the production of the so-called fluff or Automotive Shredder Residue (ASR). Due to its materials, it is assumed that all its mass constitutes ASR which is landfilled. Data used for the EOL modelling are reported in (Table 6).

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[6] http://www.woodforce.com/

Table 12 Technical data referring to car model equipped by the pedal box

Data	Unit	Quantity
Vehicle model:	-	Jeep Renegade 1,4 MultiAir Longitude (1368 cm3, 103 kW)
Vehicle mass:	kg	1320
Emission stage (e.g. EURO5):	-	EURO6
Vehicle fuel consumption (mixed urban-extra):	l/100km	5.1
CO_2 emissions:	g/km	140
FRV value:	l/100 km×100 kg	0.12

3.2.3. Chassis and suspension

Two different components belonging to the chassis and suspension system were analysed.

Cross member

The environmental impacts of a Front McPherson suspension cross member produced by Magneti Marelli was carried out. In particular a traditional design, based on steel, is compared with two innovative solutions (Table 13). The traditional design is constituted by several sub-components, all of them made with steel, thus requiring welding (arc and spot welding method) of multiple parts. Then an electrolytic process of cataphoresis for the final painting stage is performed. The first innovative solution compels one-piece unitary structure of primary Aluminium which is first melted and then treated in the casting machine. The second innovative solution is a co-moulded part consisting of a rigid composite moulded frame and aluminium inserts for the attachments during assembly on the vehicle.

Table 14 shows technical data referring to car model equipped by the cross-member, the modelling has been developed according to fuel reduction value approach described in Annex A.

For both solutions the EOL scenario considers that the cross member remains on the vehicle, thereafter it is led to the shredding and post-shredding treatments. After the shredding the so-called fluff or Automotive Shredder Residue (ASR) is processed to separate pure ferrous materials and non-ferromagnetic materials from a mixture of different materials (i.e. plastics, fibres, glass, elastomers). The first flow is intended to be recycled whereas the second to be landfilled. Data used for the EOL modelling are reported in Table 6, all the energy consumption are allocated according to the mass fraction of the component.

Table 13 Data on mass, materials and technologies for the cross member solutions (Magneti Marelli 2016b)

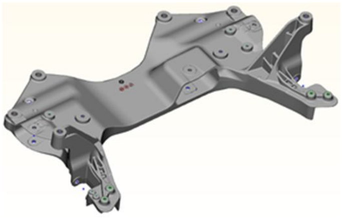
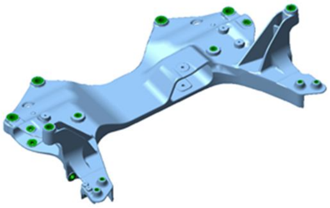
	Mass [kg]	**Materials**	**Technologies**
Light solution 1			
Single part	---	Aluminium	Casting and machining
Total	15.7 (- 18%)		
Light solution 2			
Central frame	8	Vinyle ester-SCF53	Co-moulding
Inserts	1.4	Aluminium	
Total	9.4 (- 51 %)		
 Solution 1		 Solution 2	
Ref. solution			
Several mono-material parts	---	Steel	Casting and welding, painting
Total	19		

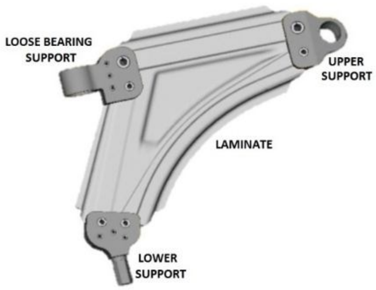
Table 14 Technical data referring to vehicle model equipped by the cross member

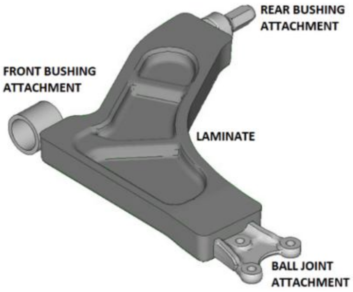
Data	**Unit**	**Quantity**
Vehicle model:	-	Alfa Romeo Giulietta 1.4 Turbo Gasoline 105 CV
Vehicle mass:	kg	1280
Emission stage (e.g. EURO5):	-	EURO5
Vehicle fuel consumption (mixed urban-extra):	l/100km	6.4
CO_2 emissions:	g/km	149
FRV value:	l/100 km×100 kg	0.12

Suspension arm

The suspension arm component belongs to the suspensions system module and connects the wheel to the chassis. Within the ENLIGHT project two lightweight solutions were developed, both comprise CFRP laminate with aluminium inserts, and they were compared with a steel based solution (Table 10). The main part of the lightweight solution 1 is produced by means of a fast RTM-process, representing an innovative application for the medium-scale production. Lightweight solution 2 is manufactured using an innovative technology called “Advanced Sheet Compression Moulding” (ASCM) whose main advantage is the possibility to create a strong cohesion between metallic insets and composite material during the moulding process (ENLIGHT D7.11 2016).

Table 15 Data on mass, materials and technologies for the suspension arm solutions (ENLIGHT D7.11 2016)

<table>
<tr><th></th><th>Mass [kg]</th><th>Materials</th><th>Technologies</th></tr>
<tr><td colspan="4">Light solution 1</td></tr>
<tr><td>1. Loose Bearing support</td><td>0.436</td><td>Aluminium</td><td>Forging</td></tr>
<tr><td>2. Upper support</td><td>0.346</td><td>Aluminium</td><td>Forging</td></tr>
<tr><td>3. Lower support</td><td>0.363</td><td>Aluminium</td><td>Forging</td></tr>
<tr><td>4. Laminate</td><td>0.655</td><td>Epoxy-SCF55</td><td>Resin Transfer Moulding</td></tr>
<tr><td>Total</td><td>1.8 (- 60 %)</td><td></td><td></td></tr>
<tr><td colspan="4">Light solution 2</td></tr>
<tr><td>1. Front Bushing Attachment</td><td>0.121</td><td>Aluminium</td><td>Forging</td></tr>
<tr><td>2. Rear Bushing Attachment</td><td>0.292</td><td>Aluminium</td><td>Forging</td></tr>
<tr><td>3. Ball Joint Attachment</td><td>0.257</td><td>Aluminium</td><td>Forging</td></tr>
<tr><td>4. Laminate</td><td>1.14</td><td>Vinyl ester-SCF53</td><td>Advanced Sheet Compression Moulding</td></tr>
<tr><td>Total</td><td>1.8 (- 60 %)</td><td></td><td></td></tr>
<tr><td colspan="2">


Solution 1</td><td colspan="2">


Solution 2</td></tr>
<tr><td colspan="4">Ref. solution</td></tr>
<tr><td>Steel</td><td>---</td><td>---</td><td>Forging</td></tr>
<tr><td>Total</td><td>4</td><td></td><td></td></tr>
</table>

The suspension arm is mounted over an electric vehicle, therefore the use stage modelling is developed according to the approach described in Annex A. The two EOL scenarios are: a "current" scenario, based on shredding and post-shredding treatments; a "future" scenario where shredding is followed by advanced post-shredding technologies; indeed dismantling was not considered a valid option due to the place of the suspension arm which would require too labour intensive process. Data used for the EOL modelling are reported in Table 9.

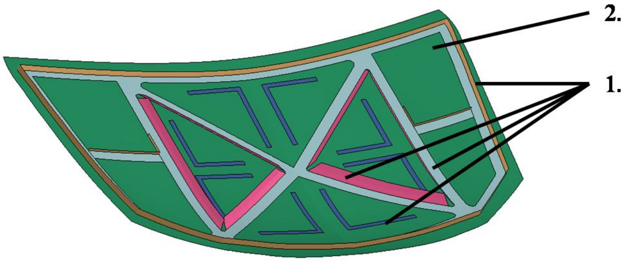
3.2.4. **Closure**

Two different components belonging to the closure system were analysed.

Front hood

The environmental impacts of two design solutions for a front hood was carried out. In particular a traditional design, based on steel, is compared with a lighter solution made with aluminium and CF-resin (Table 16). The alternative solution, developed in the framework of ENLIGHT project, was studied in its main parts: 1) Inner part; 2) Outer part.

Table 16 Data on mass, materials and technologies for hood design solutions

	Mass [kg]	**Materials**	**Technologies**
Light solution			
			
1. Inner part	1.66	Resin Epoxy CF70 WT	Compression Moulding
2. Outer part	3.16	Aluminium	Stamping
Total	4.82 (-58%)		
Ref. solution			
1. Inner part	7.18	Steel	Stamping
2. Outer part	4.36	Steel	Stamping
Total	11.54		

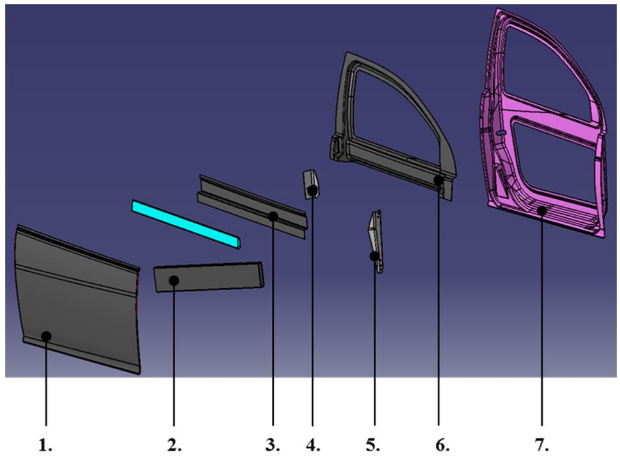
In particular the reinforcement consists in CF woven tape, an innovative reinforcement based on Uni-Directional (UD) tapes TeXtreme® whose application in normal vehicle was particularly studied in the ENLIGHT project, and more details are reported in the project deliverable (ENLIGHT D7.2 2016).

The hood is mounted over an electric vehicle, therefore the use stage modelling is developed according to the approach described in Annex A; the EOL stage is analysed according to two scenarios: a "current" scenario, based on shredding and post-shredding treatments; a “future” scenario where shredding is substituted by dismantling, and advanced post-shredding technologies are assumed (Table 9).

Front door

The environmental impacts of two design solutions for a front door was carried out. In particular a traditional design, based on aluminium and steel, is compared with a lighter solution made with aluminium and CF-resin (Table 16). The alternative solution, developed in the framework of ENLIGHT project, was studied in its main parts: 1) Inner part; 2) Outer part.

Table 17 Data on mass, materials and technologies for door design solutions (ENLIGHT D7.3 2016)

	Mass [kg]	Materials	Technologies
Light solution			
			
1. Door outer skin	1.02	PA410-CF60 WT	Thermoforming
2. Intrusion Beam	4.46	PA410-GF60 UD	CFP-Airborne
3. Waist Rail Reinforcement	0.24	PA410-CF60 WT	CFP-Airborne
4. Latch Reinforcement	0.07	Aluminium	Metal Stamping
5. Hinge/Intrusion Beam Reinforcement	0.23	Aluminium	Metal Stamping
6. Door upper close out panel	0.55	PA410-CF60 WT	Thermoforming
7. Door Inner	1.24	PA410-CF60 WT	Thermoforming
Total	7.81 (-16%)		
Ref. solution			
Aluminium parts	8.29	---	Stamping
Steel parts	0.14	---	Stamping
Aluminium component	0.81	---	Casting
Total	9.24		

The composite materials used are TeXtreme® laminate based on carbon fibre reinforced UD tapes or glass fibre with DSM EcoPaxx® PA410 as matrix. The PA410 from DSM is currently 70% bio-based and can be reinforced with either continuous glass or carbon fibre, more details are reported in the project deliverable (ENLIGHT D7.3 2016). The door is mounted over an electric vehicle, therefore the use stage modelling is developed according to the approach described in Annex A; the EOL stage is analysed according to two scenarios: a "current" scenario, based on shredding and post-shredding treatments; a "future" scenario where shredding is substituted by dismantling, and advanced post-shredding technologies are assumed (Table 9).

3.3. Data collection

The database for environmental assessment currently present some lack concerning materials (i.e. composite) and manufacturing technologies involved in the components lightweighting. Also processes representing the EOL technologies are generally not so detailed. Within the relative projects, those case studies gave the opportunity to review database (GaBi in particular) and literature concerning composite production (both fibres and matrix) and related manufacturing processes, and, when possible, to collect primary data thank to the collaboration of companies.

Overall, the accuracy of data collection, especially regarding the manufacturing stage, supports the idea that such stage (energy consumption) represents a low contribution if compared to the material and use stage ones (Das, 2011; Raugei et al., 2015); nevertheless this should not discourage investigation on this stage in detail since non negligible effects can be observed especially when composite processes are involved (Witik et al., 2011).

All the processes involved in the LCA inventory of the case studies are summed up in Table 18, data quality and sources are reported; the main input and output flows are described for those processes developed by means of primary data. Secondary data are those retrieved from GaBi or literature, when the database was found devoid or not appropriate.

Table 18 Processes for each Life Cycle stage: source and quality of data collected

Life Cycle stage	Process	Source	Quality of data		Flows		Parameterized
			Primary	Secondary	Input	Output	
Materials Manufacturing	Acrylic binder	GaBi		X	-	-	-
	Aluminium sheet	GaBi		X	-	-	-
	Aluminium extrusion profile	GaBi		X	-	-	-
	Aluminium ingot	GaBi		X	-	-	-
	Carbon Fibre	GaBi		X	-	-	-
	Epoxy resin production	GaBi		X	-	-	-
	PA410	GaBi		X	-	-	-
	Secondary ingot casting (Al)	(U. S. Department of Energy 2007)		X	Al ingot; Electricity; scraps secondary Al; thermal energy oil; Thermal energy natural gas	1 kg Al ingot	Yes
	Steel billet	GaBi		X	-	-	-
	Steel cast part alloyed (automotive)	GaBi		X	-	-	-
	Vinyl Ester	(Roos and Szpieg 2012)		X	Cobalt; Acetic acid; Alkyl benzene; Epoxy resin; Methyl methacrylate; Methylene diphenyl diisochyanate; Styrene; Electricity	Waste; 1kg Vinyl Ester	No

Life Cycle stage	**Process**	**Source**	**Quality of data**		**Flows**		**Parameterized**
			Primary	**Secondary**	**Input**	**Output**	
Materials Manufacturing	Steel cold rolled coil	GaBi		X	-	-	-
	UD Carbon Fibres 1	Material supplier	X		Electricity; pre-preg fibre; binder	scraps; 1kg UD	Yes
	UD Carbon fibres 2	Material supplier	X		CF; Electricity; binder	scraps; 1kg UD	Yes
	UD Glass fibres	Material supplier	X		Pre-preg; Electricity; binder	scraps; 1kg UD	Yes
	Glass fibres	GaBi		X	-	-	-
	Adhesive production	GaBi		X	-	-	-
	WT Carbon fibres	Material supplier	X		Electricity; UD fibres	1 kg WT fibres; scraps	Yes
Product Technologies	Advanced Sheet Compression Moulding (ASCM)	Manufacturer	X		Electricity; Pre-preg	1 kg final product; scraps	Yes
	Airborne winding/CFP	Manufacturer	X		Electricity; WT composite	1 kg final product; scraps	Yes
	Battery NMC	GaBi	X		-	-	-
	Compression moulding	(Sullivan et al. 2010)		X	Electricity; pre-preg fibre	1 kg final product; scraps	Yes
	Steel sheet deep drawing	GaBi		X	-	-	-

Life Cycle stage	**Process**	**Source**	**Quality of data**		**Flows**		**Parameterized**
			Primary	**Secondary**	**Input**	**Output**	
Product Technologies	Aluminium sheet deep drawing	GaBi		X	-	-	-
	Extrusion (Al)	(U. S. Department of Energy 2007)		X	Al ingot; Electricity; Thermal energy oil; Thermal energy natural gas	1 kg Al extruded; scraps	Yes
	Forging (Al)	Manufacturer	X		Al ingot; Electricity	1 kg final product; scraps	Yes
	Forging (Steel)	GaBi		X	-	-	-
	Plastic injection moulding part	GaBi		X	-	-	-
	Injection moulding	(Yoon et al. 2014)		X	Electricity; Plastic granulate	1 kg final product; scraps	Yes
	Metal Stamping (Al)	(Sullivan et al. 2010)		X	Al ingot; Electricity; Thermal Energy	1kg final product; scarps	Yes
	Pre-preg fibre Thermoplastic (CF)	Material supplier	X		CF; Electricity; PA410	1 kg pre-preg fibres	Yes
	Pre-preg fibre Thermoplastic (GF)	Material supplier	X		GF; Electricity; PA410	1 kg pre-preg fibres	Yes
	Pre-preg fibre Thermoset	Material supplier	X		WT fibre; Epoxy resin; Electricity	1 kg pre-preg fibres	Yes

Life Cycle stage	**Process**	**Source**	**Quality of data**		**Flows**		**Parameterized**
			Primary	**Secondary**	**Input**	**Output**	
Product Technologies	Pre-preg fibre Vinyl Ester	Manufacturer	X		CF; Electricity; Vinyl Ester	1 kg final product	Yes
	Resin Transfer Moulding (RTM)	(Suzuki and Takahashi 2005)		X	Electricity; pre-preg fibre	1 kg final product	Yes
	Rolling (Al)	(U. S. Department of Energy 2007)		X	Al ingot; Electricity; Thermal energy oil; Thermal energy natural gas	1 kg final product	Yes
	Shape Casting (Al)	(U. S. Department of Energy 2007)		X	Al ingot; Thermal energy	1 kg final product	Yes
	Steel sheet stamping and bending	GaBi		X	-	-	-
	Steel stamping	(Sullivan et al. 2010)		X	Steel cold rolled; Electricity; Thermal energy	1 kg final product; scraps	Yes
	Aluminium die cast	GaBi		X			
	Thermoforming (composite)	(Sullivan et al. 2010)		X	Electricity; WT composite	1kg final product	No
Assembly	Adhesive Bonding	(FEICA 2011)		X	Adhesive; Electricity	1m Adhesive bonding	No
	Composite spot welding	Manufacturer	X		Electricity	1 pcs	No
	Steel sheet spot welding	GaBi		X	-	-	-
	Steel sheet MAG welding	GaBi		X	-	-	-

Life Cycle stage	**Process**	**Source**	**Quality of data**		**Flows**		**Parameterized**
			Primary	**Secondary**	**Input**	**Output**	
Use stage	Use stage EV	(ALIVE - SEAM 2012)	X		Component; Electricity	1 kg component	Yes
	Use stage EV secondary effect	Internally Developed	X		Component; Electricity; Battery	1 kg component	Yes
EOL	Dismantling Components	(ENLIGHT D7.2 2016)	X		Electricity; 1kg component	1kg component	No
	Metal separation Components	(ENLIGHT D7.2 2016)	X		Electricity; 1kg component	Al recycled; Steel recycled; waste	Yes
	Pyrolysis Components	(Das 2011)		X	Composite; Thermal energy	CF recycled	Yes
	Waste incineration of plastic in municipal solid waste	GaBi		X	-	-	-
	Scrap credit Al	GaBi		X	-	-	-
	Scrap credit Steel	GaBi		X	-	-	-
	Shredding Components 1	(Tian and Chen 2014)		X	Electricity; 1kg component	1kg component	No
	Shredding Components 2	(ENLIGHT D7.2 2016)	X		Electricity; 1kg component	1kg component	No

3.4. LCA results and interpretation

The Life Cycle Impact Assessment is performed according to the CML 2001 method; impact categories have been selected according to relevance perceived by Companies involved in the ENLIGHT project and other OEMs. Therefore, results are reported according to six categories: the Global Warming Potential (GWP 100 years), Eutrophication Potential (EP); Ozone Depletion Potential (ODP); Photochemical Ozone Creation Potential (POCP); Abiotic Depletion Potential elements ($ADP_{el.}$); Primary Energy Demand (PED). Besides the importance of toxicity (for humans and ecosystems), this impact is not discussed in the case studies results interpretation for the aforementioned reason and also in order to limit the number of included impact categories and enhance results interpretation. However, impacts in terms of toxicity have been still calculated, according to the CML method, for all the case studies, in order to check if any burden shift was present. Furthermore, toxicity impact categories have been further included in the prioritizing process for TOPSIS (§6.3) and LCSA case studies (§7.1 and §7.2).

Environmental figures are shown according to the following life cycle stages: production (including raw material and manufacturing), assembly (for those component where joining techniques are applied), use and EOL.

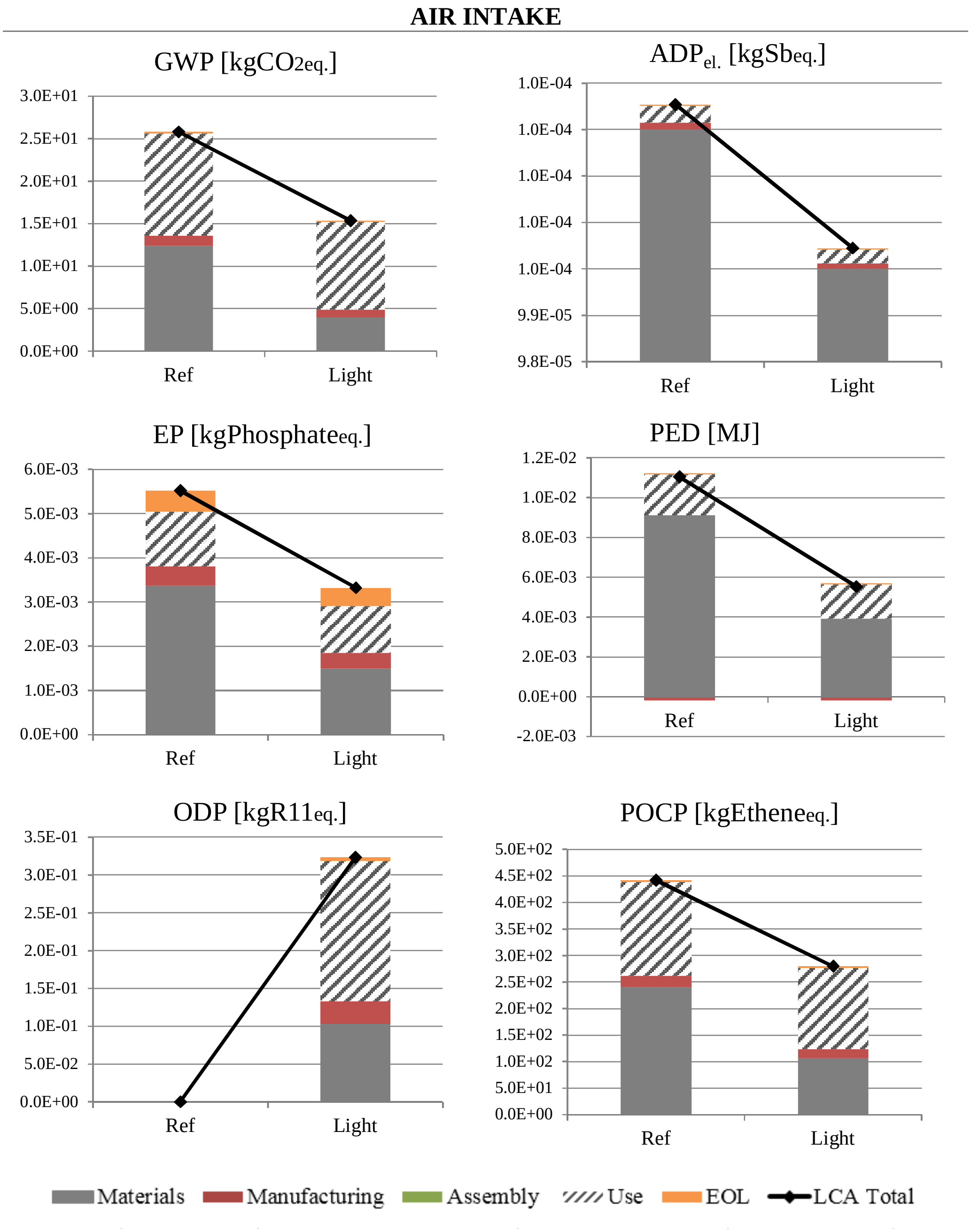


Figure 5 LCIA comparison of air intake solutions

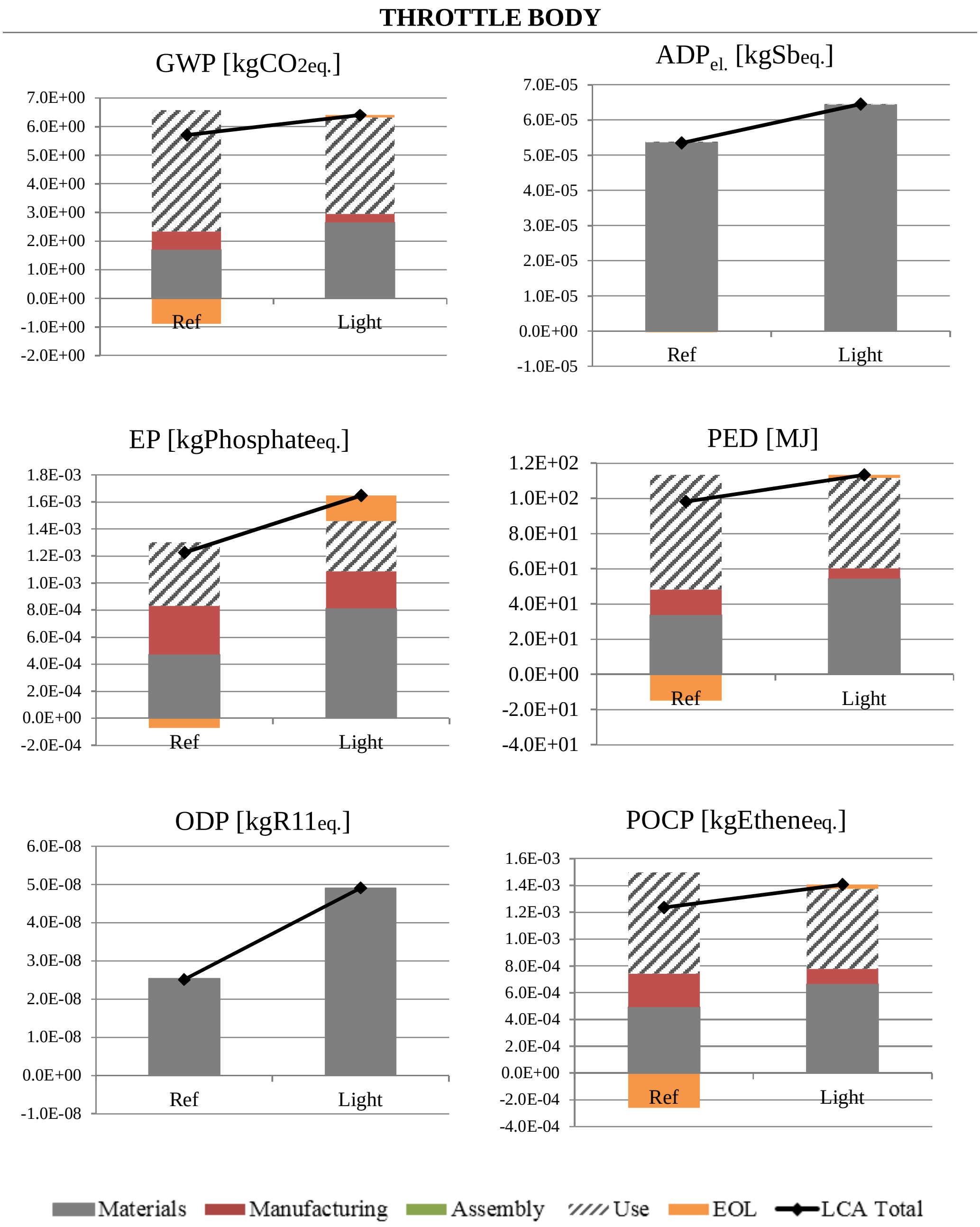


Figure 6 LCIA comparison of throttle body solutions

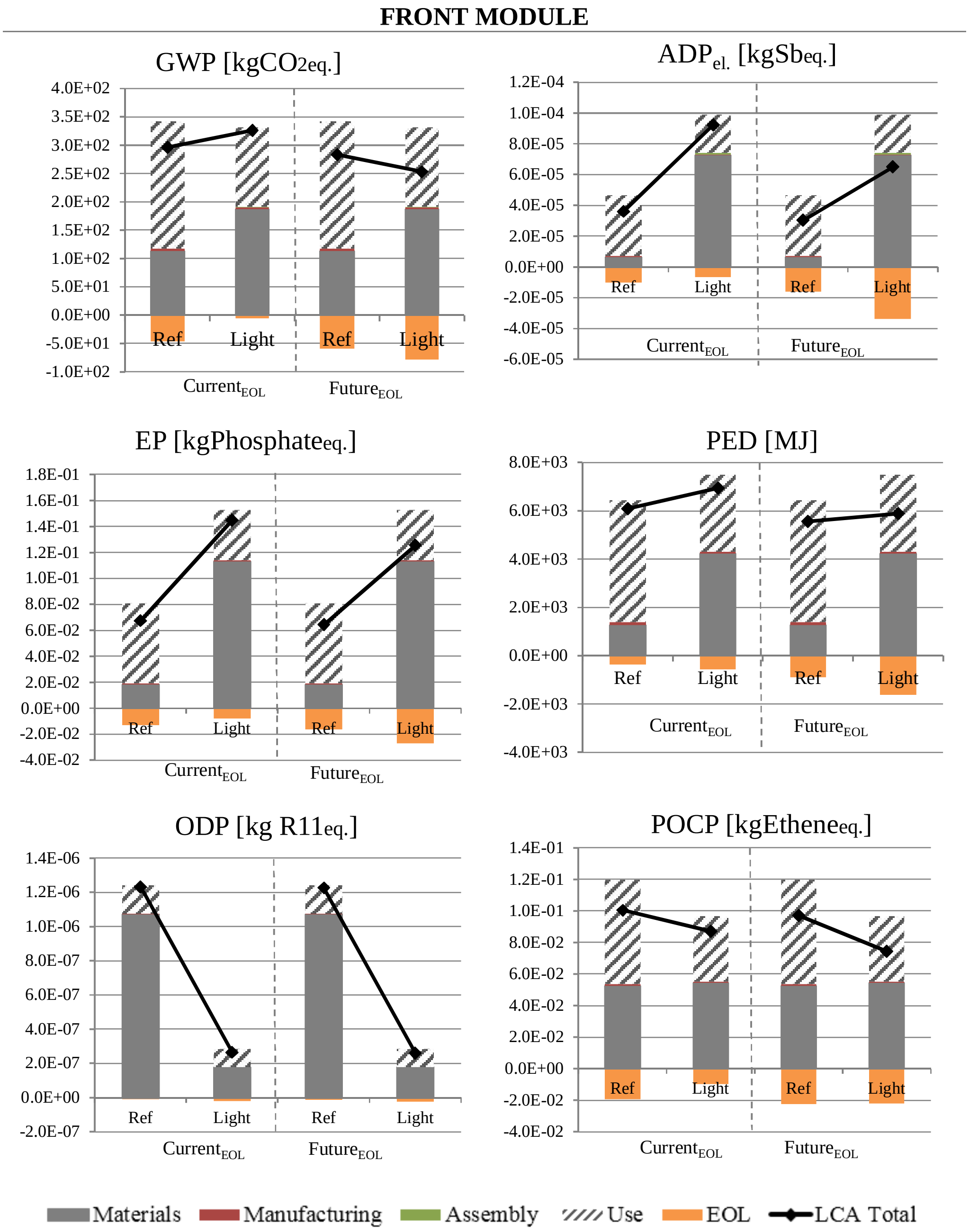


Figure 7 LCIA comparison of front module solutions

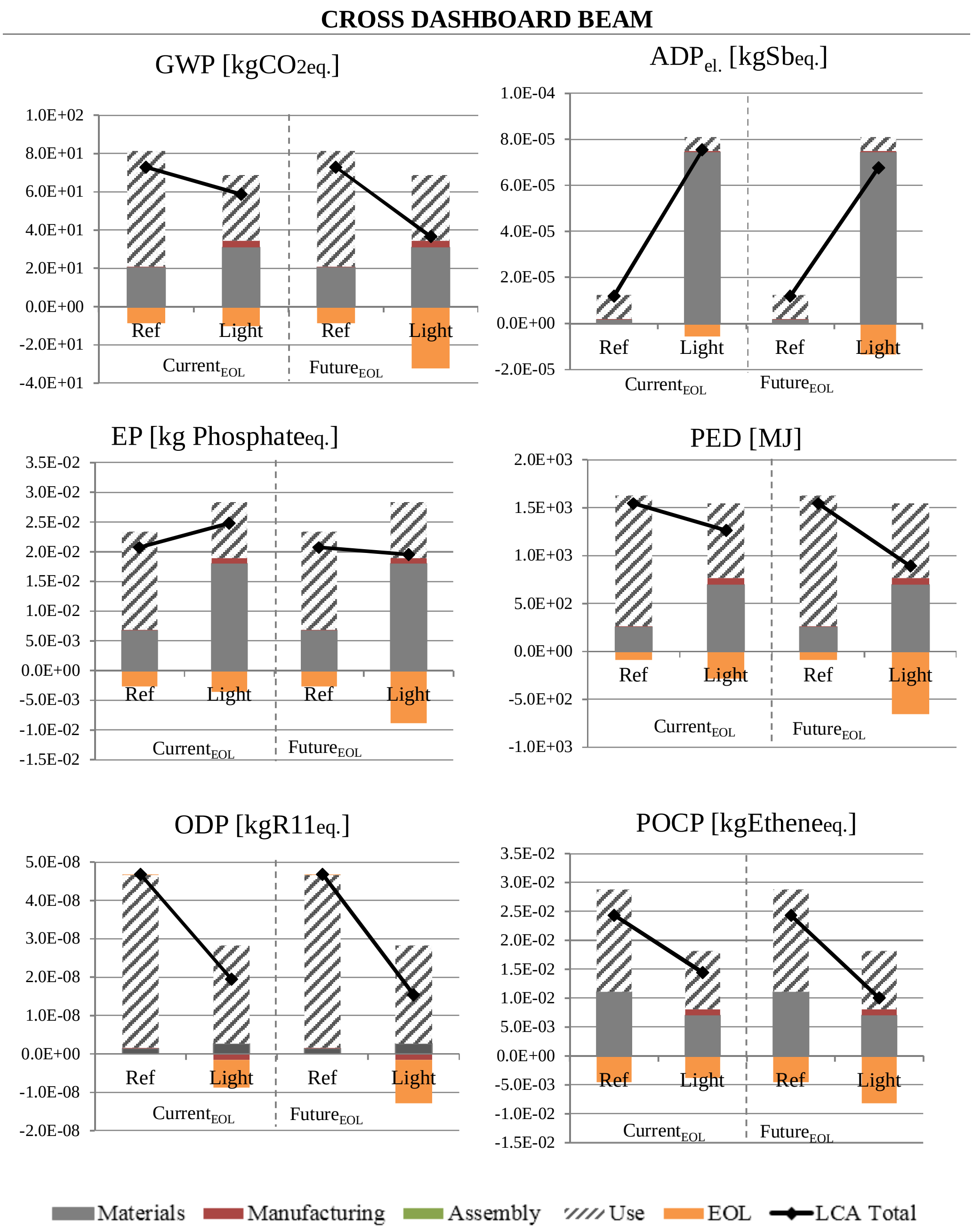


Figure 8 LCIA comparison of cross dashboard beam solutions

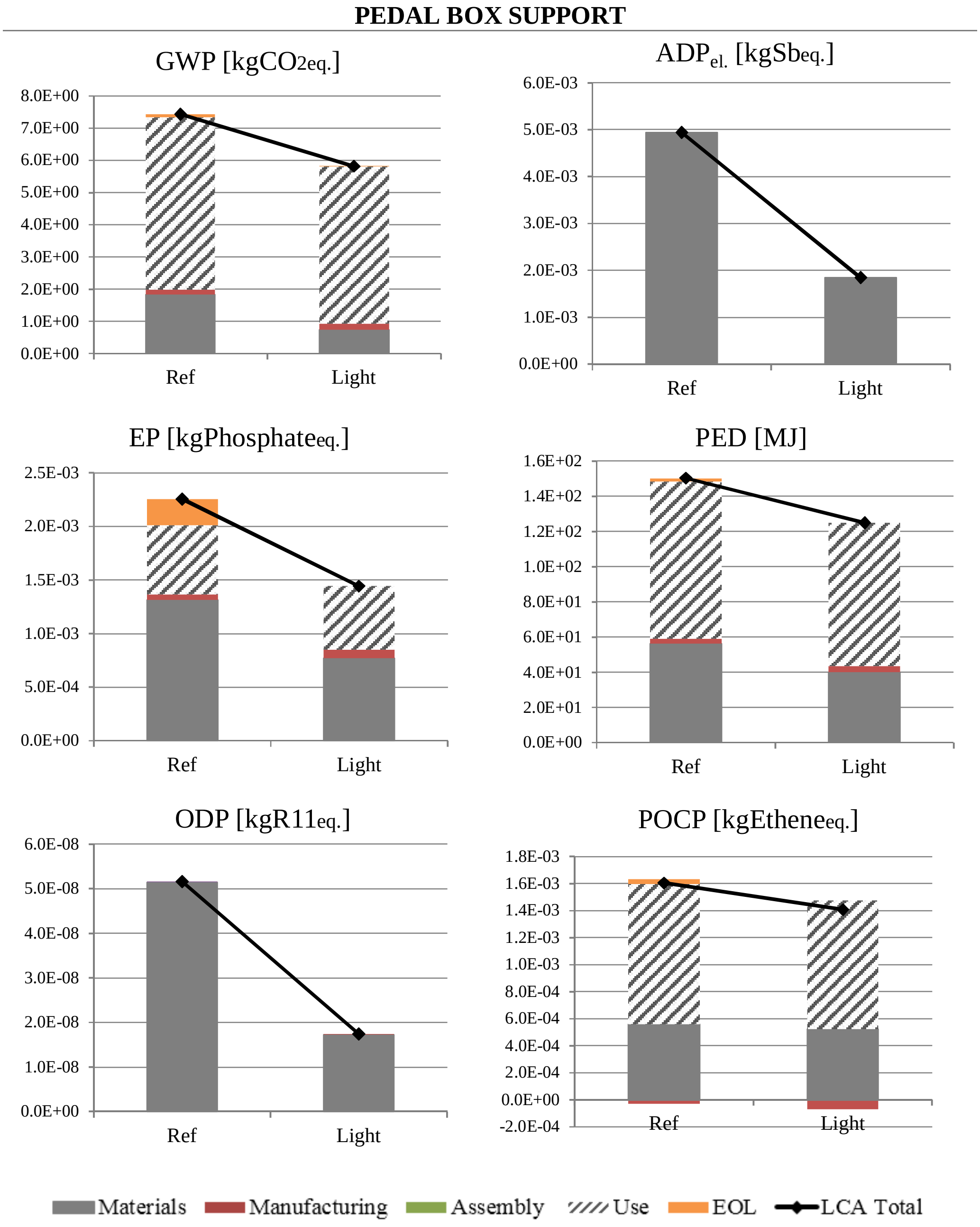


Figure 9 LCIA comparison of pedal box support solutions

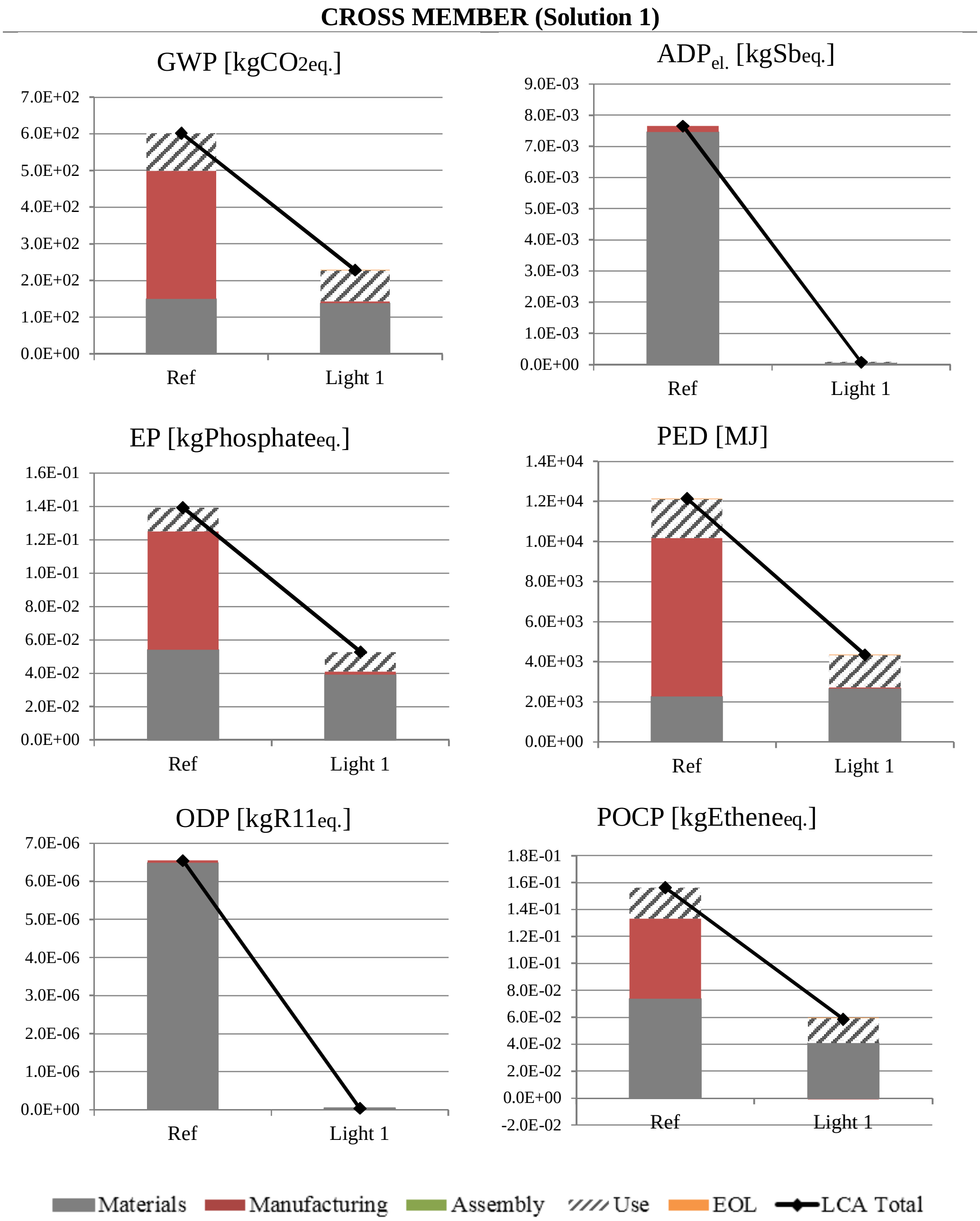


Figure 10 LCIA comparison of cross member solutions (Solution 1)

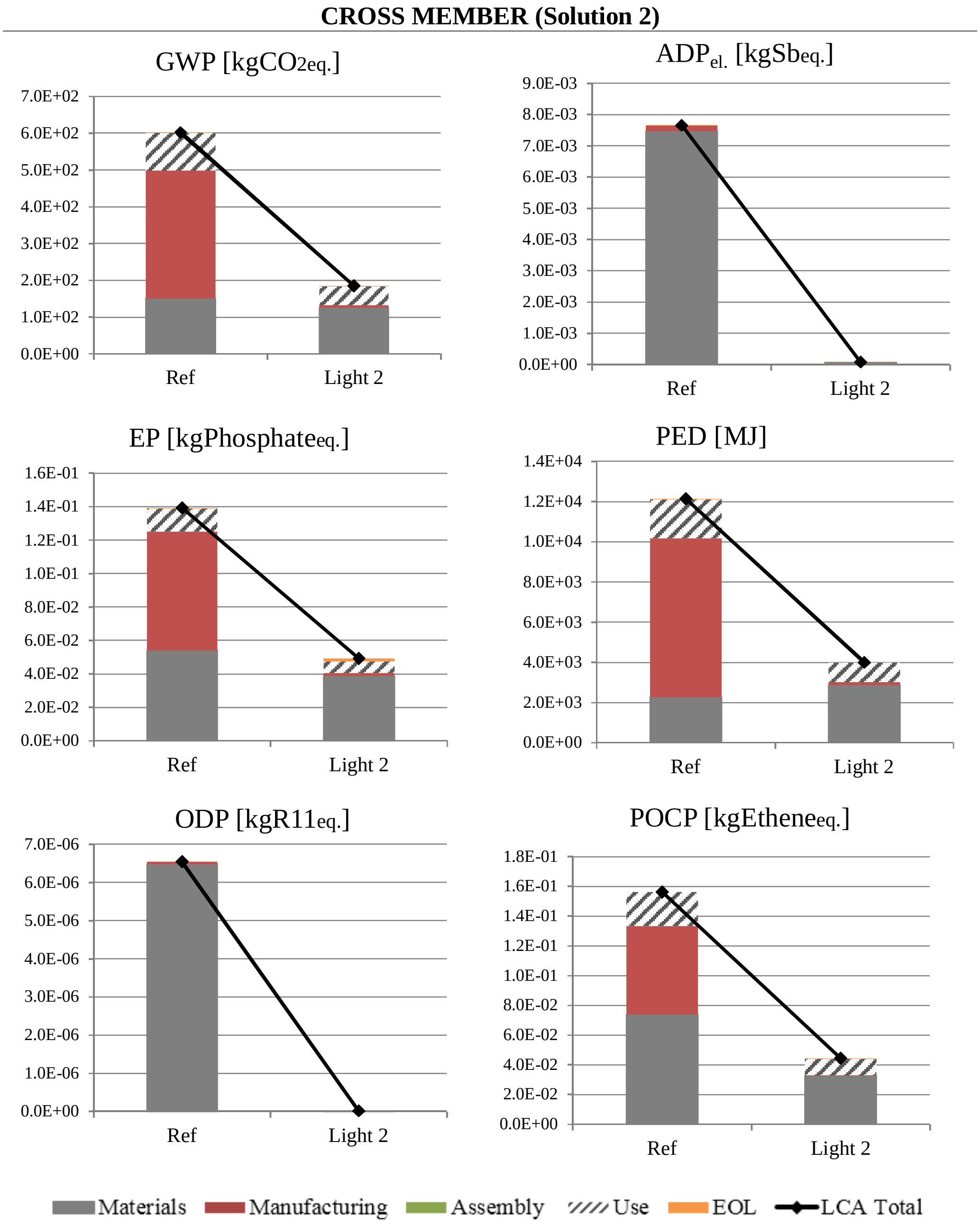


Figure 11 LCIA comparison of cross member solutions (Solution 2)

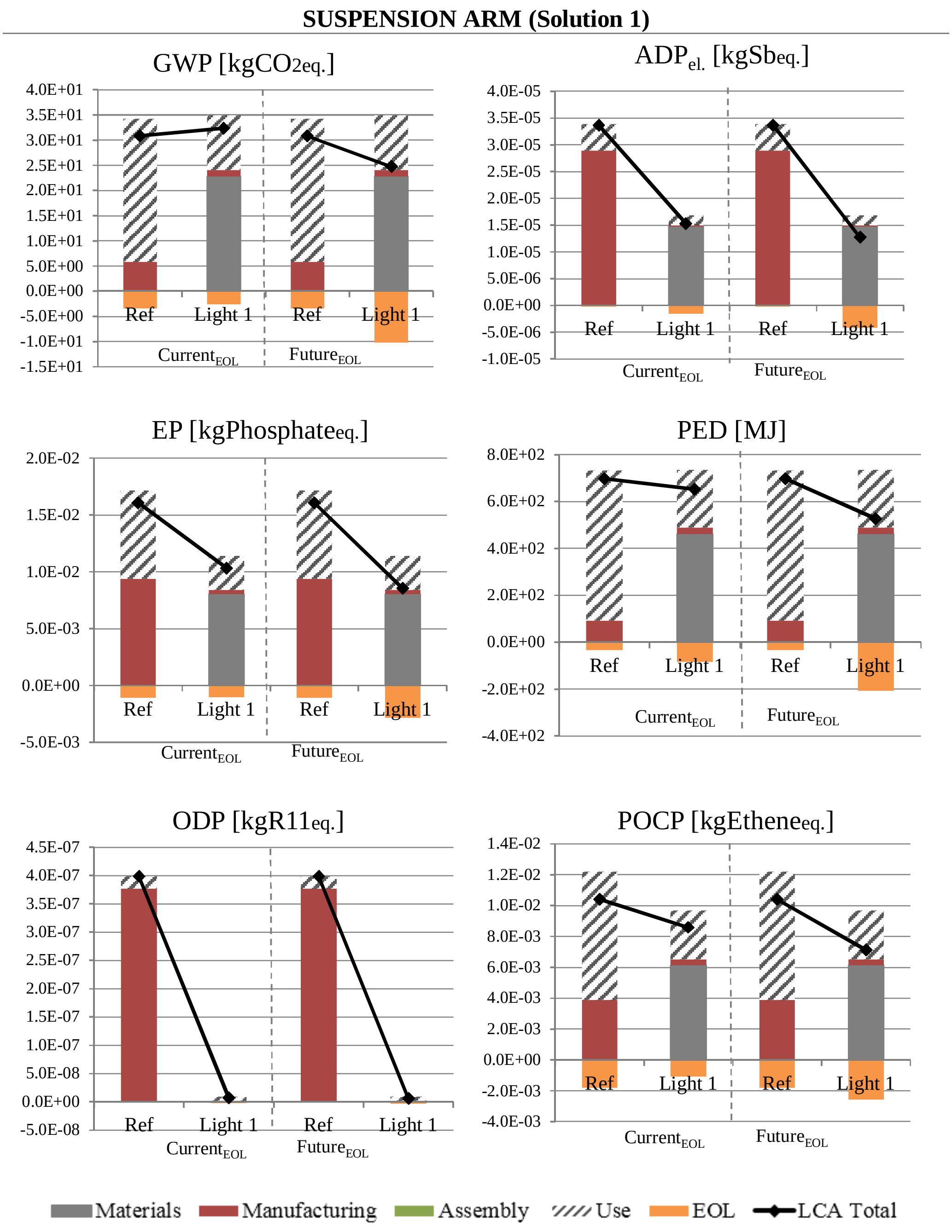


Figure 12 LCIA comparison of suspension arm solutions (Solution 1)

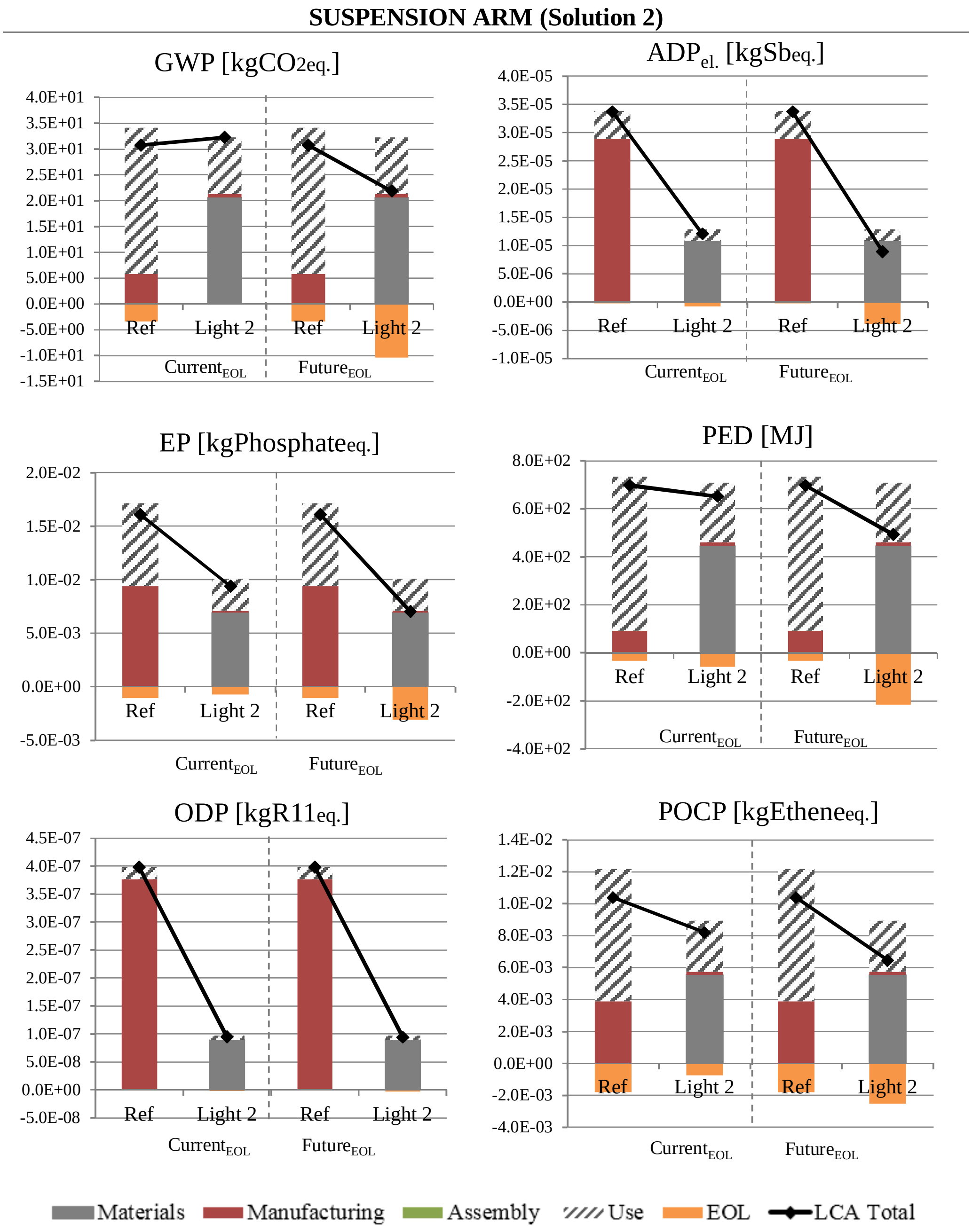


Figure 13 LCIA comparison of suspension arm solutions (Solution 2)

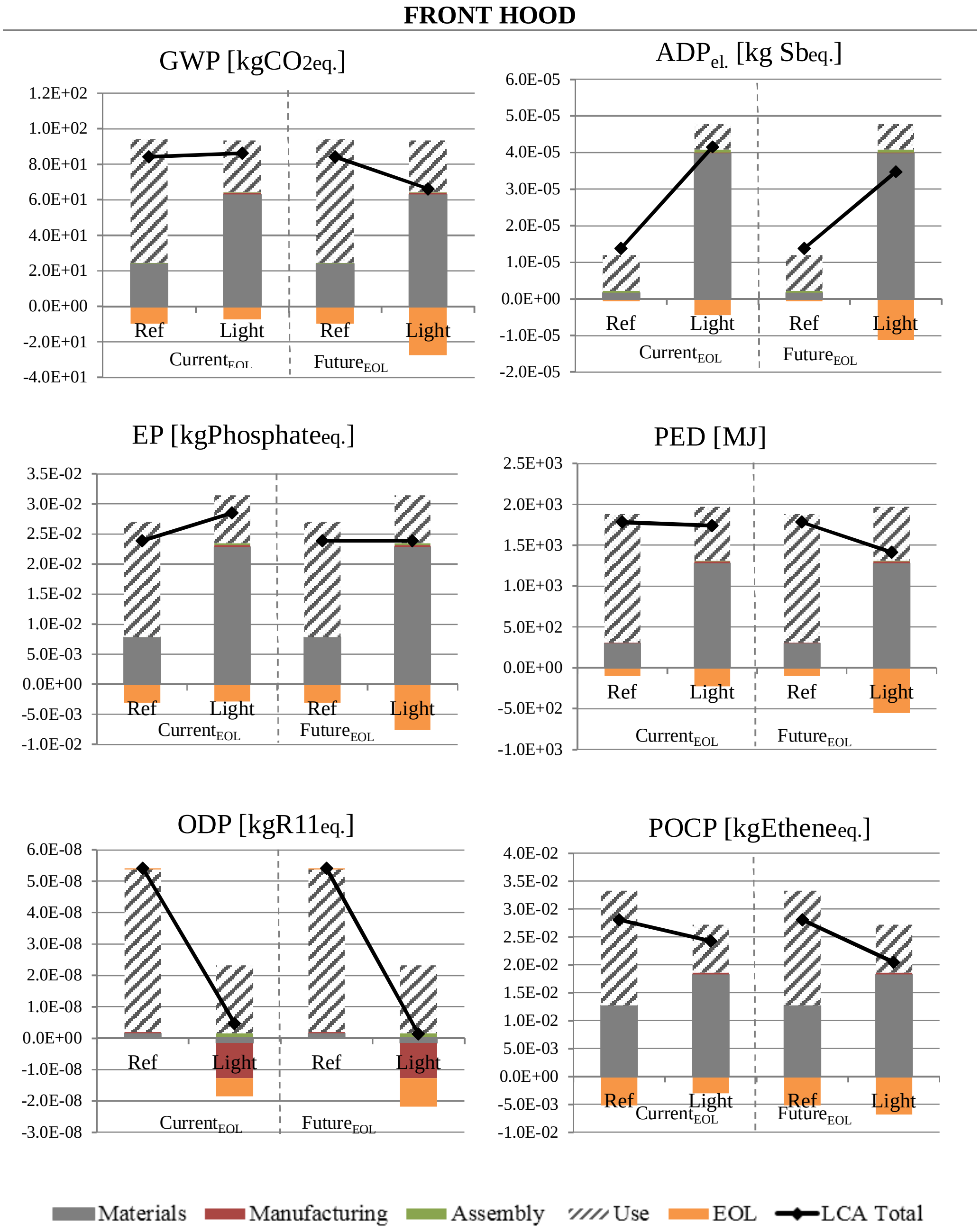


Figure 14 LCIA comparison of front hood solutions

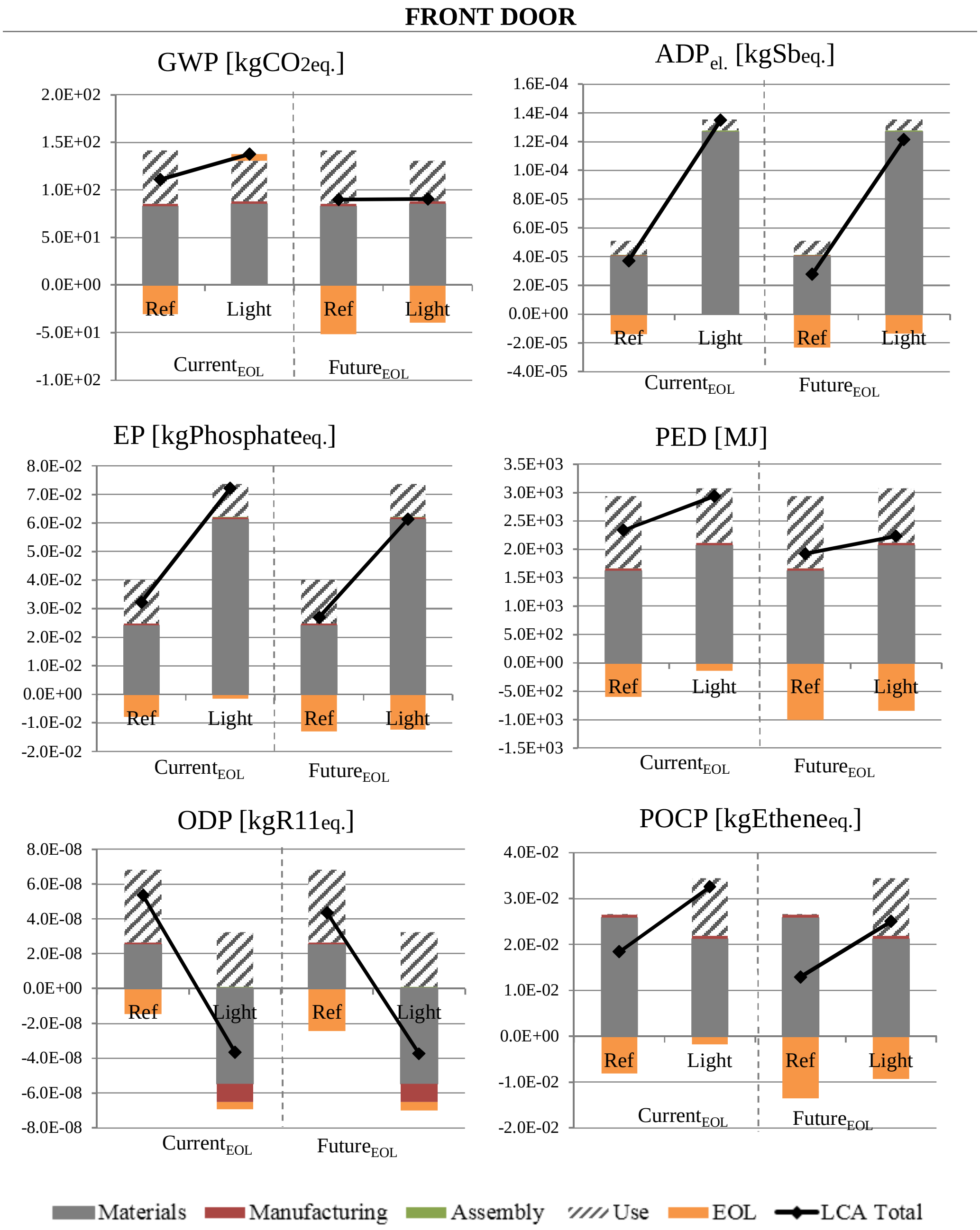


Figure 15 LCIA comparison of front door solutions

It is evident that the lightweight solutions do not provide advantages in all the studied cases and in all impact categories. Case study specific considerations are not reported in this text as the goals of this chapter is to draw more general reflections about environmental benefit and damage that can be expected from the lightweight design. More detailed results interpretation are described in the sources cited in the case studies paragraphs.

The impact from production stage was found noticeable and the raw material processing represents the largest contribution; the use stage follows. The EOL stage was found negligible when the landfill scenario is assumed, while the energy recovery from the final incineration and the materials recycling make this stage relevant in those categories sensitive to the energy process. Where alternative EOL scenarios are compared, this work demonstrates that: i) impacts due to energy consumption for final treatment (e.g. shredding) are generally negligible; ii) in some case the impacts (in terms of avoided burdens) from the final treatment could influence the overall life cycle impact and the final comparison with the reference solution in a considerable way. This is the case of front module, suspension arm and front door. Moreover the benefit achieved from advanced post-shredding treatment and materials recycling (future scenario) could be higher than the energy recovery process (assumed for the actual scenario).

As expected, comparison of environmental performances reveals that the weight reduction leads to improvements in terms of fuel consumption and gives benefits for those impact categories where the use stage is more involved (i.e. GWP, PED), whereas indicators mostly affected by the material stage (resource depletion) were found to worsen in solutions where metal is replaced with fibre-reinforced polymers.

The trade-off between use stage and material production step is confirmed by these studies, as generally stressed in the previous analysis about lightweighting (Raugei et al., 2015). In addition, outcomes confirm that a slight balance between use stage benefit and raw material stage was found concerning the GWP but it reveals more consistent regarding other environmental indicators. This demonstrates the importance of enlarging the environmental assessment to a diverse set of impact categories, in addition to the CO_2 emissions, to detect the effective advantages of a lightweight solution. In particular the resource depletion was found a challenging issue and this point could have significant implications for future policy planning regarding the automotive sector.

Overall, it is not easy to identify which design conditions/decision could lead to certain improvements in terms of life-cycle impacts, indeed many variables play a relevant role. Careful data handling is necessary to obtain clear and reliable outcomes, and in this view, data accuracy and calculation assumptions are generally claimed to be among the most important aspects when developing an LCA study in this field (Kim and Wallington, 2013b; Raugei et al., 2015; Witik et al., 2011).

The case studies have been analysed in order to identify which are the most important technical elements influencing the final environmental performance. Therefore, results interpretation was done taking into account additional indicators relating LCA results with design aspects.

The first indicator is the break-even point which could provide additional elements regarding GWP advantages/disadvantages. The breakeven analysis is used to evaluate the convenience of a solution by identifying at which vehicle’s life distance the lightweight solution could give environmental benefit if compared to the reference one; GWP is normally used for the environmental part since it is particularly influenced by the use stage (Witik et al. 2011). Indeed, also economic break-even analysis can be carried out, thus providing a way to compare and integrate environmental and economic assessment of a given solution (Delogu et al. 2016).

All the case studies demonstrated that the several impact categories have different behaviour; to better investigate these findings a second indicator, which relates delta mass with delta impact of a set of n impact categories i= {1, 2, …, n} , is calculated (equation 1).

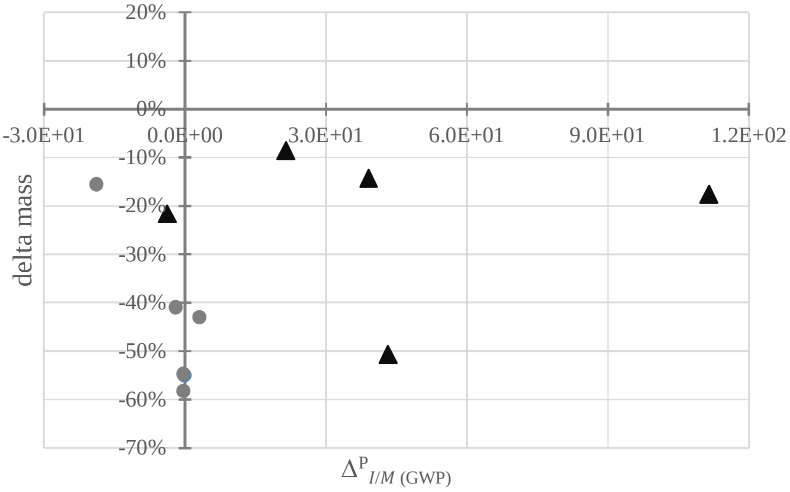
$$\Delta_{I/M}^{P} = \frac{delta_{impact}}{delta_{mass}} = \frac{impact_{LC\ Ref.} - impact_{LC\ Light}}{mass_{Ref.} - mass_{Light}} \qquad (1)$$

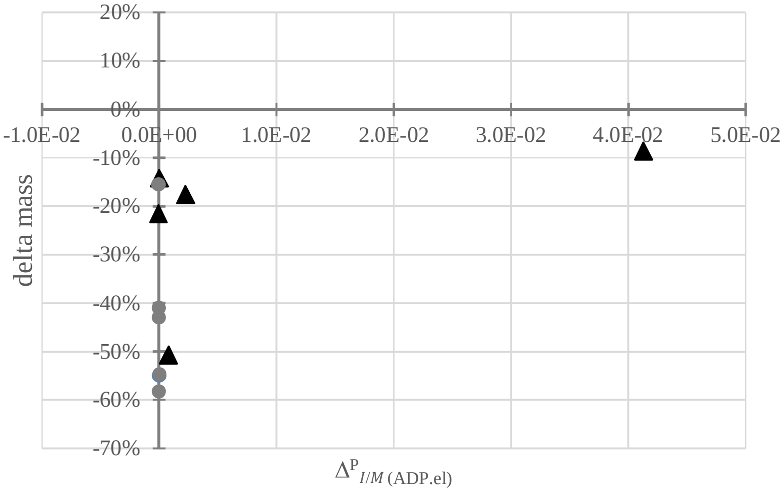
When $\Delta_{I/M}^{P}$ is >0 it means that the lightweight solution provides improvements, whereas when it is <0 then it does not.

In particular, this indicator has been calculated for three impact categories, as the most representative for the trade-off between use stage and production stage: GWP, PED, ADP$_{el}$.

Those case studies supported the idea that vehicle propulsion system, material pairs and mass reduction are the design elements influencing the final results. Therefore, the relationships between these three design elements and the two additional indicators – break-even point and $\Delta_{I/M}^{P}$ – are analysed.

First the link between mass reduction and $\Delta_{I/M}^{P}$ is evaluated (Figure 16); in these graphs also the influence of the different propulsion system is represented by means of different markers: black triangle and grey dot correspond to case studies of ICE and EV respectively. Results show that a link between mass reduction value (delta mass) and $\Delta_{I/M}^{P}$ values cannot be observed, whereas a trend between $\Delta_{I/M}^{P}$ values and propulsion system can be seen. In fact, especially for GWP and PED, the ICE case studies gain positive delta impact values, and generally higher that the ones of EVs. These findings suggest that a better performance can be achieved when the lightweight solution is applied for ICE vehicles.





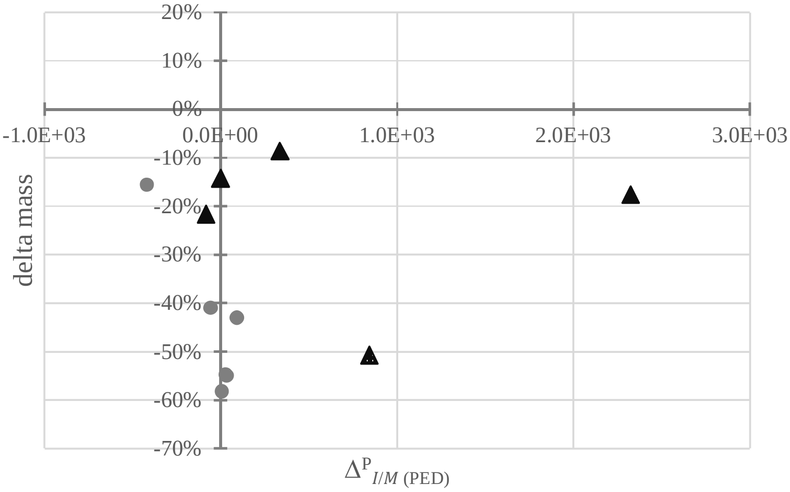


Figure 16 Relationship between delta mass, $\Delta^P_{I/M}$ (GWP, ADP$_{el.}$, PED) among case studies (black triangle: ICE vehicle case; grey dot: EV case) and propulsion system

Secondly, the relations between break-even point, delta mass and propulsion system are shown in Figure 17. The majority of lightweight applications to ICE vehicle show a break-even point equal to zero, meaning that the light solution is better, in terms of GWP, since the beginning of the life span because its production stage has already lower impact than the reference solution. On the other hand, the lightweight solutions for EV provide break-even points generally higher than the assumed vehicle life span (150,000 km).

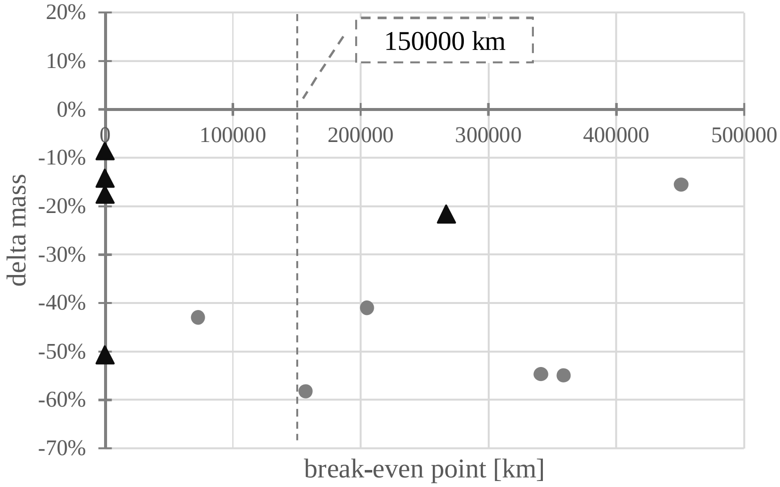
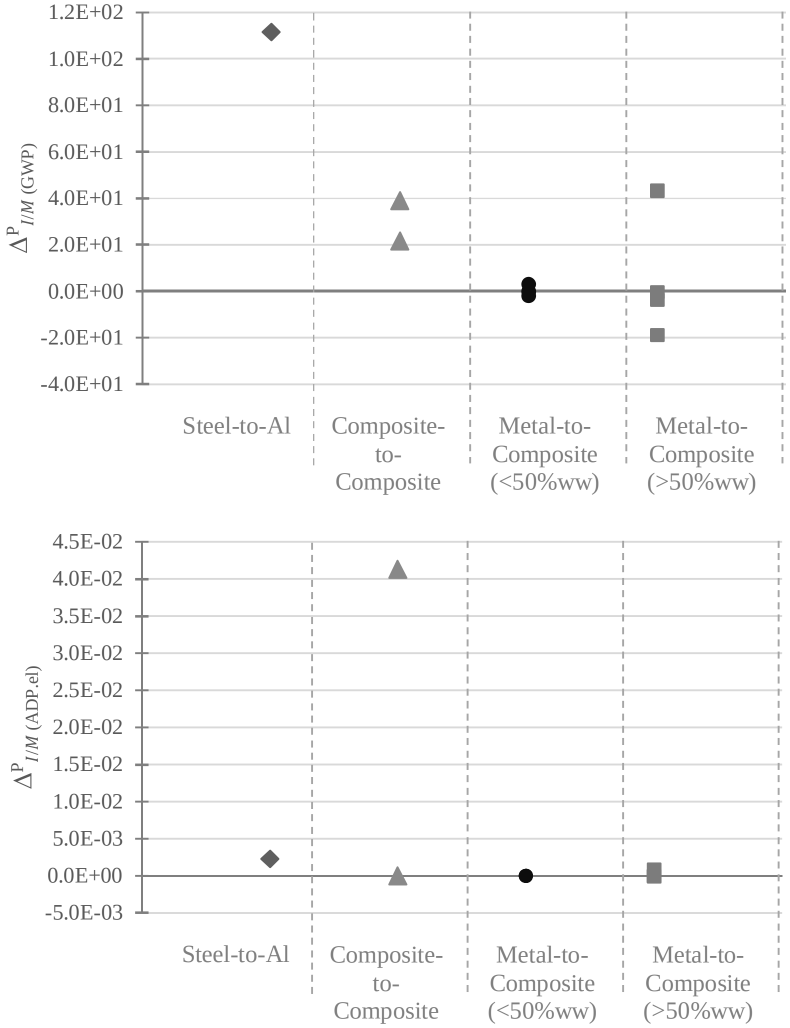


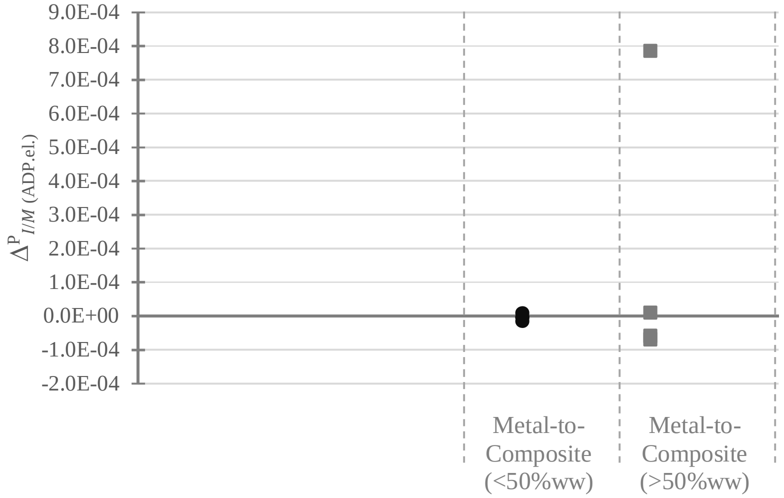
Figure 17 Relationships between delta mass, break-even point and propulsion system among case studies (black triangle: ICE vehicle case; grey dot: EV case)

Breakeven analysis is generally developed taking into account production and use stage only, however also EOL stage is candidate to be included; in this study all the break-even points are calculated taking into account the EOL stage, and the actual scenario is assumed in the case of alternative scenarios (Figure 17). Those studies demonstrate the break-even point is sensitive to this stage, both in a positive or negative sense. In some case the inclusion of EOL effect produce the decrease of break-even point value in favour of the lightweight solution (e.g. cross dashboard beam), whereas in other cases including the GWP impact of this stage makes increasing the break-even point in favour of the reference solution, this is because the reference solution is expected to have higher benefit from metal recycling (e.g. front module).

The material pairs can be considered another significant element; among the studied case studies, four classes have been identified: Steel-to-Al; Composite-to-Composite; Metal-to-Composite (<50%ww); Metal-to-Composite (>50%ww). The first represent the situation when steel is replaced by aluminium; the second includes those cases when a given composite type is replaced by another one (in terms of matrix or fibres). Then the third and the fourth class stand for those cases where a metal-based solution is replaced by an hybrid solution made with metal parts (generally aluminium) and composite elements; since the composite amount is generally considered an hotspot, two cases are distinguished by considering its mass contribution to the final lightweight solution mass (higher or lower than 50%).

Thirdly, the relationship between material pairs and $\Delta^{P}_{I/M}$ (GWP, ADP$_{\text{el.}}$, PED) is analysed (Figure 18). As it can be observed, when lightweight involves materials from the same class (Steel-to-Al and Composite-to-Composite) positive values of $\Delta^{P}_{I/M}$ are found, thus proving the new solution to be better than the reference one (Figure 18). When the design changes from a metal-based solution (typically steel-based) to a hybrid solution the final results is found more uncertain and it is not possible to expect benefit a priori (Figure 18). In addition, the higher the composite quantity the higher the uncertainty about advantages from lightweighting in a life cycle perspective.





(Excluding Steel-to-Al and Composite-to-Composite values)

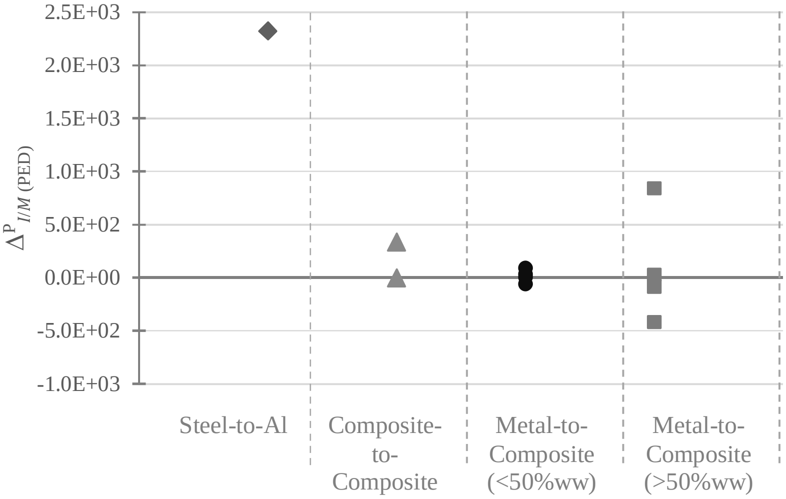


Figure 18 Relationship between material pairs and $\Delta^{P}_{I/M}$ (GWP, ADP$_{el.}$, PED) among case studies

The analysed design parameters, break-even point values and $\Delta^{P}_{I/M}$ (GWP, ADP$_{el.}$, PED) values of LCA case studies are summed up in Table 19. The relationship between three design parameters - vehicle propulsion system, material pairs and mass reduction - and the advantages/disadvantages stemmed from the lightweighting have been deeply investigated by means of two additional indicators (break-even point and $\Delta^{P}_{I/M}$), and are reported in Figure 16, Figure 17 and Figure 18. Such results could be of relevance during an early design phase, in fact they supported the idea that vehicle propulsion system and material pairs are the design elements mostly influencing the benefits achievable by means of material substitution, taking into account the component life cycle. Especially for GWP and PED, the

ICE case studies gain positive $\Delta_{I/M}^{P}$ values, and generally higher that the ones of EVs. These findings suggest that a better performance can be achieved when the lightweight solution is applied for ICE vehicles. The breakeven analysis confirmed such results, in fact the majority of lightweight applications to ICE vehicle shown better break-even point figures. The material pairs was found to be another significant elements, in fact when lightweighting involves materials from the same class (Steel-to-Al and Composite-to-Composite) the new solution is always better than the reference one. On the contrary, when the design changes from a metal-based solution (typically steel-based) to a hybrid solution, the achieved benefit are more uncertain. In this sense, the amount of composite was found a discriminating factor for the lightweighitng potentials.

Overall, results from Figure 16, Figure 17 and Figure 18 are one of the first example, to the best knowledge of the author, of LCA results interpretation by means of hybrid indicators; moreover they provide first insights concerning the influence of the vehicle propulsion system to the final lightweighting effects. Indeed, increasing the number of case studies would allow to provide more precise results; therefore further investigations are suggested.

Table 19 Design parameters, break-even point values and $\Delta^{P}_{I/M}$ (GWP, $ADP_{el.}$, PED) values of LCA case studies

Component name	Material pairs	Propulsion system	Ref. mass [kg]	Light mass [kg]	$\Delta^{P}_{I/M}$ (ADPel.)	$\Delta^{P}_{I/M}$(GWP)	$\Delta^{P}_{I/M}$(PED)	Break-even point [km]	delta mass
Air intake	Composite-to-Composite	ICE	1.87	1.60	1.16E-05	3.91E+01	2.06E-02	0	-14%
Throttle body	Metal-to-Composite (>50%ww)	ICE	0.86	0.67	-5.94E-05	-3.75E+00	-8.26E+01	267012	-22%
Front module	Metal-to-Composite (<50%ww)	EV	37.12	21.90	-3.69E-06	-2.01E+00	-5.68E+01	204853	-41%
Cross dashboard beam	Metal-to-Composite (<50%ww)	EV	10.00	5.70	-1.46E-05	3.12E+00	9.13E+01	72706	-43%
Pedal box support	Composite-to-Composite	ICE	0.87	0.79	4.13E-02	2.15E+01	3.37E+02	0	-9%
Cross member (Sol. 1)	Steel-to-Al	ICE	19.00	15.65	2.26E-03	1.12E+02	2.33E+03	0	-18%
Cross member (Sol. 2)	Metal-to-Composite (>50%ww)	ICE	19.00	9.36	7.86E-04	4.33E+01	8.44E+02	0	-51%
Suspension arm (Sol. 1)	Metal-to-Composite (<50%ww)	EV	4.00	1.80	8.47E-06	-1.24E-01	3.41E+01	358707	-55%
Suspension arm (Sol. 2)	Metal-to-Composite (>50%ww)	EV	4.00	1.81	9.85E-06	-3.75E-01	2.80E+01	341032	-55%
Front hood	Metal-to-Composite (<50%ww)	EV	11.54	4.82	-4.13E-06	-2.79E-01	6.24E+00	156911	-58%
Front door	Metal-to-Composite (>50%ww)	EV	9.25	7.81	-6.85E-05	-1.88E+01	-4.20E+02	450803	-16%

4. Life Cycle Costing: review and proposal of an approach for the lightweight design

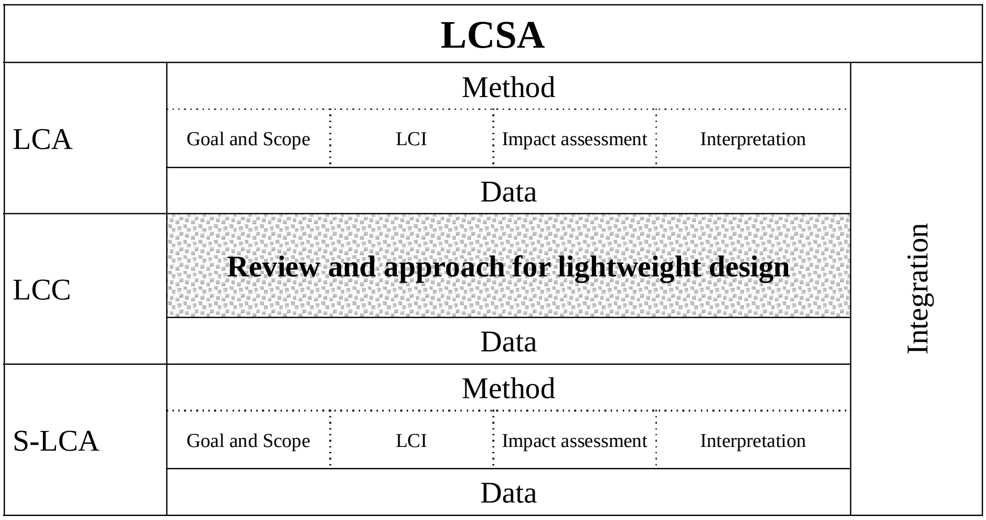


Figure 19 Scheme of research contributions to LCSA methodology: LCC review and proposal of an approach for the lightweight design

Unlike the LCA, there are currently no standards available for the LCC of products or services in a sustainability context. With the exception of the building sector, for which the ISO 15686-5:2008 Buildings and constructed assets -- Service-life planning -- Part 5: Life-cycle costing has been developed, the main references for the application of the methodology are represented by the Code of Practice on Environmental Life Cycle Costing (Swarr et al. 2011), and by the publication of Hunkeler and colleagues (2008), who paved the road for the Code of Practice.

In the automotive product life cycle many actors are involved (i.e. materials suppliers, components producer, vehicle producer, user) and the decision of implementing a lightweight solution or not does make sense only if the production cost is compared with the benefits that this solution will produce in the use stage (in favour of the consumer).

This research aims at providing consistent and comprehensive approach for the life-cycle based economic assessment of lightweight solutions for vehicle components, in the Life Cycle Sustainability framework (Figure 19).

This is achieved by (1) a literature review to identify how the main methodological and practical aspects are dealt with in the applications related to the automotive sectors (cfr. § 4.1, 4.2), (2) discussion about LCC settings from the Code of Practice, in the light of automotive lightweighting (cfr. § 4.3 – 4.6), (3) a LCC study concerning vehicle component lightweight in order to evaluate applicability and critical methodological aspects (cfr. § 4.7) (Figure 19).

4.1. LCC methodology overview

Life Cycle Costing (LCC) is a methodology of calculating the total cost of a product (goods, services, technologies) induced throughout its life cycle. It is often used for supporting the decision process about design, development and purchase of products, processes or activities. Overall, five basic life cycle stages significant for the LCC can be identified (Huppes et al. 2004):

- Research, development and design;
- Primary production;
- Manufacturing;
- Use and maintenance;
- Disposal management.

Many LCC approaches and variants exist; according to (Huppes et al. 2004) three main types of LCC can be distinguished based on their historical background:

- Cost Benefit Analysis LCC (CBA-LCC);
- Budget LCC and LCC as a Managerial Cost Accounting;
- LCC in a LCA context (LCA-LCC).

The LCA-type LCC originates from LCA panorama and attempts to include economic analysis to the environmental one. Common features are the use of functional unit, the product system description, based on units/processes and flows (i.e. energy, materials, waste). Nevertheless, some open issues still exist to make LCC a fully applicable methodology. The cost modelling and the analysis perspective are some examples. Being the LCA approach based on steady-state model, some authors argued that even the cost approach would be based on steady-state costs. Moreover, since the costs encountered along the product life cycle are generally sustained by different actors, the difference between purchases and sales, the value added, is a thorny aspect to be tackled. Defining the perspective of the analysis seems to be a peculiarity aspect for the LCC; its definition in the goal and scope phase could guide the following analysis assumptions and a coherent result interpretation.

In the SETAC Code of practice three different types of LCA-type LCC are proposed:

- Conventional LCC
- Environmental LCC
- Societal LCC

The difference among them is provided in Figure 20.

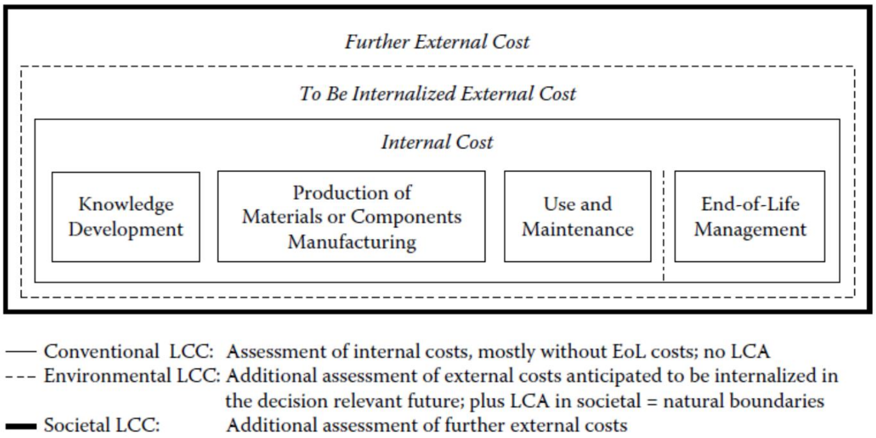


Figure 20 The three types of LCC: conventional LCC, environmental LCC and societal LCC

The differences between the several LCC variants rely on four basic dimensions (Hunkeler et al. 2008):

1. Cost categories (budget cost, personnel cost, etc.);
2. Cost bearers (producer, society, etc.);
3. Cost models (steady-state, quasi-dynamic, etc.);
4. Cost aggregation (average yearly cost, NPV, etc.).

As previously mentioned, when studying the costs of a product one may look at the cost bearer who determines what costs are to be included in the LCC analysis. (Huppes et al. 2004) identifies eight types of bearers: producer, supply chain, owner, user, group, life cycle, country's society and global society. Whereas, the Code of practice proposes three main perspectives: producer, consumer and society – according the three LCC types _ conventional, environmental and societal. The word 'perspective' is equivalent to 'bearer' concept; it is more used and for that reason it will be used in the following.

It is generally considered that in the conventional LCC the perspective of one actor is assumed, either the manufacturer or the user; whereas one or more actors connected to the product life cycle can be included in the environmental LCC (mainly manufacturers and user). In the societal LCC the perspective of the whole society is adopted (Hunkeler et al. 2008).

The third dimension of LCC is the cost-model, in particular how the time value of money is considered. Several types of models can be found (steady-state, quasi-dynamic, dynamic, etc.) (Huppes et al. 2004). The steady state model is the simplest one and neglects a time specification assuming all processes to be constant in time. A dynamic model considers the development of all variables over time, whereas a quasi-dynamic model assumes that most of the variables remain constant in time, though they allow one or more of them to vary.

Conventional and societal LCC generally apply quasi-dynamic models, while environmental LCC is generally recommended to be set up as a steady-state method in order to allow a combined use of LCC and LCA results, stemmed from steady-state environmental methods (Hunkeler et al. 2008).

The last dimension of LCC is aggregation of costs/revenues. A total value, like Net Present Value, or a yearly flow, like an average cost per year are some examples (Hunkeler et al. 2008). The aggregation of LCC results is generally not handy but it can be recommended or not depending on the intended final use (Martinez-Sanchez 2015).

Cost discounting is another important aspect which has been addressed in the Code of Practice (Swarr et al. 2011); according to Hunkeler et al. (2008): "The reasons for discounting depend very much on the question to be addressed". Overall, the Code of Practice considers inconsistent and not recommended the discounting of results for the eLCC, while it is recommended for conventional LCC and societal LCC.

Among the three proposed approaches – conventional LCC, environmental LCC and societal LCC - the most appropriate one was identified as the environmental LCC when the cost assessment is developed and integrated to the environmental LCA or even within a sustainability assessment (Schau et al. 2011).

The environmental LCC is defined as "An assessment of all costs associated with the life cycle of a product that are directly covered by any one or more of the actors in the product life cycle (e.g., supplier, manufacturer, user or consumer, or EOL actor) with complementary inclusion of externalities that are anticipated to be internalized in the decision-relevant future (…). Environmental LCC (eLCC) has to be accompanied by a life cycle assessment and is a consistent pillar of sustainability." (Hunkeler et al. 2008).

As an LCA-type LCC, the main phases of the eLCC study are the ones proposed the Code of Practice:

1. Goal and Scope Definition;
2. Economic Life Cycle Inventory;
3. Interpretation;
4. Reporting and Critical Review.

4.2. Review of Life Cycle Costing applications in the automotive sector

The economic characteristics of automotive products have been addressed in literature, related either to the whole vehicle (Ogden et al. 2004; Hunkeler et al. 2008; Wong et al. 2010; Kim et al. 2011; Cicconi et al. 2014) or to specific components (Bubeck 2002; Ungureanu et al. 2007; Roes et al. 2007; Khoonsari 2009; Witik et al. 2011; Schau et al. 2011). In the first case, LCC is applied to compare and identify the economic benefit expected from different power train systems or a different material. The aim of applying the LCC to a single module is often to compare different design solutions in terms of economic expenditures during the production stage but also in terms of benefit during the use stage (Witik et al. 2011).

Traditionally, LCC has the potential to support Design for Environment (DfE) actions since it could provide cost transparency beyond the direct development and production cost (Schmidt 2003). However, some challenges of the economic assessment of products, including the automotive ones, are:

- General uncertainties about costs incurred in some life cycle stages (i.e. disposal/recycling costs) (Schmidt 2003) and also about environmental costs (i.e. air-pollutant damage costs, GHG costs) (Ogden et al. 2004);

- Needs of specific knowledge and experience to interpret LCC results; LCC is considered “an expert tool to be used by financial or life cycle experts” (Schmidt 2003);
- Variety of approaches, especially regarding cost categories, system boundaries assumptions and perspective (Hoogmartens et al. 2014).

Indeed the review could only refer to studies and practices publically available which are not necessarily the same as the internal practice of OEMs. In fact, since sustainability and economic viability represent competition elements, procedures as well as data are expected to be often confidential information.

In the automotive sector LCC applications present a great variety in terms of level of development, types, dimensions and objective.

Overall, LCC is considered a decision-making tool; indeed some authors carried out LCC studies to support consumers investment decisions (Cicconi et al. 2014) or to evaluate the life cycle cost to reduce Green House Gasses emissions relative to lightweight solutions (Kim et al. 2011). In other cases it is used to assess the economic part of a wider sustainability assessment of product (Schau et al. 2011).

Concerning types and methods, the following approaches have been encountered: Total Cost of Ownership (Ungureanu et al. 2007); Full Cost Accounting (Jasinski et al. 2015); cost-benefit analysis is developed to provide an economic assessment of vehicle lightweight solutions (Kim et al. 2011). Lloyd and Lave (2003) and Song (2009) evaluated economic and environmental impacts of materials for automotive products by using an economic input-output model. Only few examples of the LCA-type LCC (i.e. conventional LCC and environmental LCC) can be found (Schau et al. 2011). They specifically refer to the Code of practice to develop and select the appropriate LCC structure. Other studies generally brought up LCC method but do not discuss the methodological aspects in details (Ungureanu et al. 2007; Cicconi et al. 2014). As a consequence, some typical elements like functional unit, perspective and system boundaries are seldom discussed.

Overall, those works addressing LCC of whole vehicle generally adopt a user’s perspective and consider the following cost categories: initial cost, operation cost and maintenance cost. Costs related to ownership taxes and car insurance are generally neglected due to a high variability depending on countries and because they are not expected to influence the comparison between vehicle models in a relevant way (Cicconi et al. 2014). Even maintenance costs are often excluded because uncertain or not influencing (Ogden et al. 2004). When different propulsion systems are compared then the societal perspective is also evaluated, therefore externalities are also addressed (Ogden et al. 2004; Wong et al. 2010).

Externalities are the incurred costs of direct and indirect long-term economic, social and environmental impacts, that are priced in monetary units, due to their to-be-internalized character in the decision-relevant future (Hunkeler et al. 2008; Wong et al. 2010). Although they are mentioned to be very important, they are rarely included in a comprehensive way since are difficult to be assessed (Cicconi et al. 2014). According to (Hunkeler et al. 2008) externalities include concepts like willingness to pay or the cost of preventing the effects; therefore their accounting and monetization is extremely uncertain. They are generally considered only in societal LCC, while externalities accounted in the eLCC are those expected to be internalised and borne by any of the actors in the life cycle period.

Although they are mentioned to be very important, they are rarely included in a comprehensive way for two main reasons: they have a quite wide meaning and are difficult to be managed (Cicconi et al. 2014). According to (Hunkeler et al. 2008) externalities include concepts like willingness to pay (for avoiding these effects) or the cost of preventing the effects; therefore their accounting and monetization is extremely uncertain.

The literature review showed that in the automotive field, externalities generally comprise environmental costs as pollutant emissions and vehicle EOL costs, both as treatment costs (i.e. incineration) (Roes et al. 2007) and recycling cost net of income (Cicconi et al. 2014). However, road accidents, noise and traffic congestion can be considered other relevant externalities involving society (Jasiński et al. 2016).

Carbon emissions and other emissions responsible for the air quality (NO_X, SO_2, PM, etc.) are regarded as an indicator of the environmental and societal cost, but also scraps and waste recycling/disposal are relevant cost to be taken into account. Currently these environmental costs are not yet internalized, this means that they are not covered by tax and subsidy mechanisms involving neither producers nor consumers. According to the European directive, CO_2 emissions fees are expected to be paid by those car manufacturers who will produce vehicle exceeding the limits (2009/443/EC); despite the limit any case or reference on how to deal with this fee are not available in literature.

As a consequence, only when a society point of view is adopted, then the externalities are addressed in details: air-pollutant damage costs (i.e. SO_2, NO_X), greenhouse gas emissions damage costs, oil supply insecurity costs (Ogden et al. 2004; Wong et al. 2010). It is claimed that when different alternative automotive engine/fuel options are compared a high role is played by "the valuations that society assigns to externalities, via appropriate regulations or taxation, rather than the relative externalities considered in isolation of other costs." (Ogden et al. 2004); in fact when such externalities are internalized, the most advanced vehicle options provide lower life cycle cost values than typical new cars, for which externalities generally account for about half of the LCC value (Ogden et al. 2004).

Those studies dealing with components generally use life cycle cost model focused on manufacturing and develop the study according to two perspectives: manufacturer and user (Khoonsari 2009; Schau et al. 2011). In some cases, when the user perspective is assumed the component acquisition cost is used as representative for the whole production stage, while in other studies the direct production expenditure is summed up to the use stage and EOL (Witik et al. 2011). Overall, LCC is used to compare traditional materials for a given component (i.e. steel) with innovative and lightweight ones (i.e. Aluminium, composites) with the aim of evaluating the component manufacturing costs and the expected use stage cost reduction due to mass saving (Ungureanu et al. 2007; Witik et al. 2011).

Overall market prices of all material and energy inputs are generally used (Roes et al. 2007; Witik et al. 2011) and a key aspect generally discussed in the LCC studies is the discount rate for costs or revenues that occur in the mid- to long-term future. For the automotive products discounting can be considered relevant for the use stage, which generally is assumed 10 years at least, and the EOL stage costs. However, according to (Hunkeler et al. 2008), the discounting should be developed consistently with the LCC type; in particular it is recommended only in the case of conventional and societal LCC, but it is considered inconsistent/not recommended in the environmental LCA. Three of the automotive LCC case studies claimed to not perform discounting (Roes et al. 2007; Hunkeler et al. 2008; Schau et al. 2011), while other performed Net Present Value calculation for the use stage (fuel cost) and EOL treatment costs (Ogden et al. 2004; Khoonsari 2009; Wong et al. 2010; Kim et al. 2011; Witik et al. 2011; Cicconi et al. 2014).

The integration of environmental and economic criteria with the traditional requirements in product design is gaining vital importance for many companies, for this reason some authors attempt to provide explicit and transparent structure to calculate LCA and LCC of a given product/system (Simões et al. 2013; Heijungs et al. 2013). Besides that, very few example of combined LCC and LCA exist in the literature for the automotive sector. Typically, economic assessments are carried out separately from LCA, thus equivalence in the system boundaries definition, functional unit and other assumptions are not discussed. The integration of economic and environmental aspects encountered along the life cycle of an automotive product is discussed only in a few cases (Roes et al. 2007; Witik et al. 2011; Schau et al. 2011). In these cases LCA and LCC are based on the same goal and scope settings but the final results are presented separately. Among automotive case studies, an attempt to connect LCA and LCC findings is offered by (Witik et al. 2011) who calculates the breakeven point values corresponding to CO_2 and total life cycle cost. This analysis enables to compare alternative solutions and select the best option in terms of trade-off between cost and environment. (Jasinski et al. 2015) analysis is based on a different approach where economic, environmental and social aspects are combined by means of the unique metric of monetary value. This approach will be better discussed in the following paragraph concerning sustainability assessment based on Triple Bottom Line theory.

When environmental and economic assessments are combined, special attention should be given to avoid double-counting (Martinez-Sanchez et al. 2015), that is double counting of externalities in LCC (i.e. CO_2 emissions cost) and the complementary LCA (i.e. CO_2 effects in terms of GWP) (Hunkeler et al. 2008). The following statement is expressed in the Code of Practice “In conclusion, it seems appropriate to base LCC, as long as it is framed by independent other assessments such as LCA, on the assumption of a primarily unregulated market, even if this includes some double counting for the external effects actually internalized via taxes or subsidies and introduces additional uncertainties. Double counting is, clearly, an issue to minimize, though its avoidance in total is unlikely, and one should be aware of instances where it occurs and ensure it is consistent for all alternatives being compared.” (pp. 37). This is a thorny aspect which is seldom discussed in literature (Schau et al. 2011) therefore further research will be required.

In conclusion the main key aspects, stemmed from the literature, to consolidate LCC are: i) the scope of the assessment and the related perspective, ii) the time period taken into account for the several market price, iii) the use or absence of discounting to deal with long time horizons (Hoogmartens et al. 2014), iv) the development of cost categories tailored to the specific sector (Martinez-Sanchez et al. 2015; Jasinski et al. 2015), v) integrating LCC in the sustainability framework (Schau et al. 2011; Simões et al. 2013).

Table 20 Review of LCC case studies in the automotive sector

Reference	**Object of analysis**	**Perspective**	**Discounting**	**Externalities**	**Reference to the Code of practice**
(Cicconi et al. 2014)	vehicle	User (consumer)	yes	not included	no
(Hunkeler et al. 2008) Cap. 7	vehicle	User (consumer)	no	not included	yes (conventional LCC)
(Khoonsari 2009)	component (BiW)	Manufacturer (but also others involved in use and EOL stages)	yes	EOL costs	no
(Kim et al. 2011)	vehicle	Producer and consumer	yes	not included	no
(Ogden et al. 2004)	vehicle	Society	yes	air-pollutant damage costs (i.e. SO2, NOx), GHG damage costs, oil supply insecurity costs	no
(Roes et al. 2007)	component (automotive panels)	not specified	no	waste incineration	no
(Schau et al. 2011)	component	Producer (remanufacturer) and consumer	no	not included	yes (environmental LCC)
(Ungureanu et al. 2007)	component (BiW)	not specified	not specified		no
(Witik et al. 2011)	component	not specified	yes	EOL costs	no
(Wong et al. 2010)	vehicle	Societal and consumer	yes	CO_2 emissions cost	no

Table 21 Life cycle stages included in the LCC case studies of the automotive sector

Reference	**Cost categories and Life cycle** stage**s included**
(Cicconi et al. 2014)	Purchase cost, operation cost, but also social cost lead by environmental impact regarding production, use and EOL stages.
(Hunkeler et al. 2008) Cap. 7	The acquisition expense (depreciation of car, imputed interest of purchase price, and initial costs for transfer), fixed costs during the use stage (tax and insurance, rent for garage, parking fees, etc.), operating costs (for fuel, costs, washing, and general care), and maintenance (e.g., tire wear and inspection) were included
(Khoonsari 2009)	Pre manufacturing cost, manufacturing cost, use and post use costs
(Kim et al. 2011)	Acquisition and manufacturing of lightweight materials. The cost model also includes estimated producer costs for LW vehicles, fuel cost, costs to establish a collection and recycling infrastructure, sorting costs per unit, production costs of using secondary versus primary materials, and scenarios for material value at EOL.
(Ogden et al. 2004)	Vehicle first cost (assuming large-scale mass production), fuel costs (assuming a fully developed fuel infrastructure), externality costs for oil supply security, and damage costs for emissions of air pollutants and greenhouse gases calculated over the full fuel cycle.
(Roes et al. 2007)	Materials, manufacturing, use and incineration
(Schau et al. 2011)	Component acquisition cost, cost of spare parts, cost of cleaning of parts, labor cost, transport, packaging, fuel, repair and maintenance, insurance, license and fees, disposal.
(Ungureanu et al. 2007)	Pre-manufacturing, manufacturing, use and post-use
(Witik et al. 2011)	Materials & manufacture, vehicle use, EOL treatments
(Wong et al. 2010)	Acquisition cost and registration fees, operation and external costs

4.3. Scope of the assessment

The literature review showed that cost categories included in the analysis are seldom described in a detailed way. As a consequence, a structured approach for the application of LCC in the lightweighting case studies is lacking, since it is not clear which are the most important cost to be included, which parameters and data need to be collected to enhance an assessment as much accurate as possible. Moreover, the economic assessment of lightweighting solutions in the automotive sector struggles with a high heterogeneity due to the complexity of the product (number of materials, processes and actors involved).

Within a R&D workflow, LCA and LCC could provide consistent results only when geometry, materials and technologies are fixed and the prototype, and its technical performances, are tested. For this reason an attempt was done to organise the assessment in terms of identification of the cost categories, and their calculation, reflecting the following situation: economic assessment during the prototype phase of a component belonging to different vehicle systems (i.e. suspension system, powertrain), based on estimate for a real production scale (>50 000 parts per year).

4.4. Perspective

With the ultimate goal of applying LCC within a LCSA study, the environmental LCC type is selected.

In the automotive product life cycle many actors are involved: materials suppliers, components producer, vehicle producer, user and actors dealing with vehicle EOL treatments (disposal, recycling but also reselling) (Jasiński et al. 2016).

In the lightweight design context the decision of implementing an innovative solution or not does make sense only if the production cost is compensated by the benefits that this solution will produce in the use stage.

In this sense the user perspective seems the most appropriate one; however the consumer does not directly experience the single component but the whole vehicle. For that reason a user perspective appears not completely adequate. As soon as the assessment is applied to the comparison of lightweight solutions for automotive components, the manufacturer perspective is the most relevant but it would not take into account use stage cost and EOL costs which are borne by different actors. Indeed the cost of these life stages directly depend on decisions during the design phase.

For this reason in this research a ‘hybrid perspective’ is proposed since costs directly supported by the manufacturer[7] (i.e. production and transport) are summed to the cost for the user .More precisely the ‘hybrid perspective’ concept would represent a ‘user perspective’ where the production cost is assumed in place of the acquisition cost. In such a way the producer can evaluate the benefit for the consumer achieved by its higher expenditure and thus decide the proper price for the innovative solution.

Although EOL costs are not supported neither by producer nor by the user, it is important to stress that including these costs in the eLCC could be relevant since they definitely depend on the design decisions. Dealing with the EOL costs is challenging because of a great variability by Countries; moreover such information is particularly difficult to be gathered. Overall, information about waste flows from vehicle treatments is not easy to be collected; many actors are involved and a complex system does not allow a complete traceability (Berzi et al. 2013). This is particularly true when the analysis is focused on a specific component. All these reasons would support the exclusion of the EOL costs from the analysis since only estimate could be collected and used in the calculation. Considering that automotive producer are however involved in the EOL aspects by the ELVS directive it seems appropriate to push practitioners to deal with also EOL costs in their LCC analysis. In conclusion, in this research the ‘hybrid perspective’ would also include these expenditures.

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[7] Depending on the case study, manufacturer could be the Company dealing with component design and production or the Company dealing with vehicle production and so component assembly on the vehicle. More specifications will be given in the following case studies.

4.5. Categories and modelling of costs

The following cost categories and parameters mainly stemmed from the literature review and also personal communications with Companies of the sector. They were involved in order to select those data which definitely could be collected by a company during the early design phase (prototype) of a new product.

Cost categories are referred to the three main life cycle stages: production, use and EOL. Therefore a general eLCC formula is:

$$eLCC = C_{Production} + C_{Use} + C_{End-of-Life} \tag{2}$$

Production stage comprises materials acquisition costs, component production and assembly on vehicle.

$$C_{Production} = \sum_{i=1}^{n} C_{material\ i} + \sum_{j=1}^{m} C_{manufacturing\ j} + C_{assembly} + C_{transport} \tag{3}$$

where:

- n and m are the number of materials applied and manufacturing activities involved respectively;
- $C_{material\ i}$ is the material acquisition cost of the i-material;
- $C_{manufacturing\ j}$ is the manufacturing cost of the j-activity;
- $C_{assembly}$ is the cost for the assembly activities, depending on the case study this cost could be modelled in the same way of the manufacturing.

Component production can be modelled according to variable and fixed costs. Generally, fixed costs include machinery/equipment amortization, tools and moulds costs; whereas variable costs are energy, labour and maintenance (Ulrich et al. 2007).

$$C_{manufacturing} = C_{amortization} + C_{tools} + C_{labor} + C_{energy} + C_{maintenance} \tag{4}$$

where:

$$C_{amortization} = \frac{C_{machinery}}{N_{years\ machinery\ life}} \times \frac{1}{N_{pieces}/_{year}} \tag{5}$$

Since all the costs need to be allocated to the product, the following parameters are necessary:

- average yearly production for the allocation of the amortization cost;

- production expected during the whole life span of tools for the allocation of the overall tools costs (C_{tool*}) to the produced piece (C_{tool}) (6);

$$C_{tools} = \frac{C_{tools*}}{N_{pieces\ along\ life\ span}} \tag{6}$$

- hourly production for the allocation labour costs (7);

$$C_{labor} = \frac{C_{hourly\ labort}}{hourly\ production} \tag{7}$$

- energy unit cost (i.e. €/kWh, €/m3 methane) and energy consumption per product (from LCA) (8);

$$C_{energy} = C_{energy\ unit} \times \frac{energy}{piece} \tag{8}$$

According to personal communication with Companies from the sector, cost for machinery maintenance is generally assumed as a percentage of the total investment (i.e. 5%).

The use stage cost comprises the contribution of propulsion system and the contribution of externalities as pollutant emissions (i.e. CO_2, NO_x).

$$C_{Use} = C_{propulsion} + C_{externalities} \tag{9}$$

The maintenance cost of the component was not included since it can be hardly estimated and depends on the given component.

The cost of the propulsion can be calculated according to the model use for the LCA, i.e. a mathematical model that correlates the fuel consumption of the whole vehicle to the fuel use due to the component. The key parameters are the fuel reduction and the energy reduction for the ICE and EVs respectively. More details about the model are reported in Annex A.

$$C_{propulsion} = fuel_{\ component} \times C_{fuel\ unit} \tag{10}$$

$$C_{propulsion} = energy_{\ component} \times C_{energy\ unit} \tag{11}$$

Other key parameters for the use stage modelling are the life distance (i.e. the kilometres travelled throughout the vehicle life span) and the driving cycle; within a LCSA study they need to be set accordingly to the LCA FU (e.g. 150,000 km and NEDC New European Driving Cycle). The cost for the energy/fuel unit should necessary be assumed in accordance with the geographical scope assumed for the energy grid/supply mix in the LCA.

As for the externalities, very few reasoning can be found in the reviewed case studies, however it can be claimed that currently pollutants emissions costs are not borne by any actors (producer, consumer) but would be soon internalized so, according to the Code of Practice they should be included in the eLCC.

The EOL stage of vehicles is a complex system of several processes which generally involves different actors. Overall, three main steps are involved: decontamination (i.e. removal of battery) and dismantling of spare parts and recyclable materials (i.e. bumpers, tires, fuel tanks, glasses) performed in Authorized Treatment Facilities; shredding and recovery valuable metals; final disposal of the residual fraction, defined Automotive Shredder Residue (ASR), by means of landfill or incineration with energy recovery (Cossu et al. 2014).

Depending on the component type and its materials, different processes and activities are involved, and also costs and possible incomes from part or scrap reselling. Overall the EOL stage cost can include:

$$C_{End-of-Life} = C_{pre-treatment,\ shredding,\ post-shredding} + C_{disposal} - C_{recycled/reuse} \tag{12}$$

These costs are generally hard to be found; some values of total cost of treatment per kilogram of waste stemmed from general estimate of the sector (GHK, Bio Intelligence Service 2006)

Use stage and EOL costs are not to be discounted, according to the Code of Practice. Therefore, the life cycle costs is calculated using a steady-state model (Hunkeler et al., 2008). A discount rate can be assumed for a sensitivity analysis in order to detect its influence.

4.6. Other Goal and Scope settings

Functional unit, product function, system boundaries and product system should be defined coherently with the environmental and social assessments. More details on this aspect will be discussed in the chapter 7.

4.7. Application to a real case study: lightweighting of a suspension arm

The following case study was developed thank to the collaboration of Magneti Marelli ®. In particular the design of the suspension arm has been developed within the ENLIGHT project framework.

4.7.1. Goal and Scope Definition

The goal and scope of this eLCC study is to carry out an economic assessment of two design solutions of a suspension arm produced by Magneti Marelli ® to give insights about economic trade-off between the production cost increase and the use stage expenditure reduction during an early design phase.

The aforementioned ‘hybrid perspective’ is applied, therefore costs directly supported by the manufacturer (production and transport) are summed to the cost of the use stage and final treatment.

The FU of the study is a suspension arm, connecting the wheel with the suspension system of an electric passenger vehicle based on a Golf VI, with a life-distance of 150,000 km for 10 years. A steel based solution, suitable for a Golf VI and with a mass of 4 kg, is compared with a lightweight design based on carbon fibres composite and aluminium inserts, with a total mass of 1.8 kg. More details about the two solutions are reported in the paragraph 0. The innovative solution is expected to provide the same primary function and to complain with the mechanical and safety performances required. The product system is depicted in Figure 21, and the eLCC system boundaries comprises the following life cycle stages: material production, component manufacturing, use stage and EOL. Cost for R&D was not specifically targeted so is excluded from this analysis.

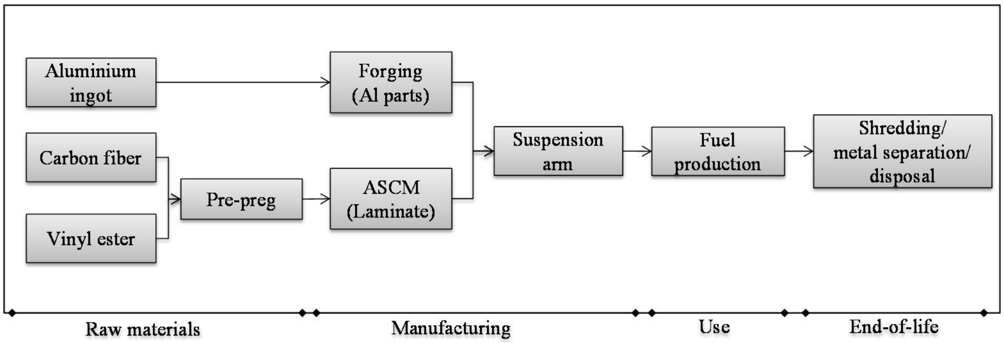


Figure 21 Product system and system boundaries suspension arm case study

4.7.2. Economic Life Cycle Inventory

Starting from the LCC formula reported in the paragraph 4.5, the life cycle inventory involved the data gathering for the following stages: material acquisition, suspension arm manufacturing, use stage, EOL.

The production cost was calculated according to the equation (2) and by means of the data reported in Table 22 and Table 23.

Table 22 Data inventory material stage suspension arm case study

Data	**Unit**	**Value**	**Source**
Reference solution			
Steel mass	kg/FU	9.98	Producer
Steel price (2016)	€/kg	1.07	Producer
Lightweight solution			
Composite mass	kg/FU	1.155	Producer
Composite price (>200 000 piece per year)	€/kg	20	Producer
Aluminium mass	kg/FU	1.64	Producer
Aluminium price	€/kg	0.5	Producer

Table 23 Data inventory manufacturing stage suspension arm case study

Data	**Unit**	**Value**	**Source**
Reference solution			
Forging (steel) machinery price	€	7,500,000	Producer
Electricity consumption for forging	kWh/piece	2.68	Producer
Wage	€/h	50	Producer
Cycle time forging (steel)	h/piece	0.0083	Producer
Electricity price (2016)	€/kWh	0.12	(Eurostat 2016a)
Lightweight solution			
ASCM machinery price	€	3,000,000	Producer
Electricity consumption for ASCM	kWh/piece	2.37	Producer
Tools price	€	1,000,000	Producer
Tools life span	piece	50,000	Producer
Forging (Al) machinery price	€	300,000	(Ulrich et al. 2007)
Electricity consumption for forging (Al)	kWh/piece	1.38	Producer
Wage	€/h	50	Producer
Cycle time ASCM	h/piece	0.083	Producer
Cycle time forging (Al)	h/piece	0.003	Producer
Electricity price (2016)	€/kWh	0.12	(Eurostat 2016a)

The main assumptions regard 10 years as machinery life span and their maintenance costs assumed equal to 5% of the total investment. Transports and assembly are not included because data were not available.

The use stage is modelled according to the EVs modelling reported in Annex A. The key parameters required are listed in Table 24.

Table 24 Data inventory use stage suspension arm case study

Data	**Unit**	**Value**	**Source**
Electricity price (2016)	€/kWh	0.12 (European average)	(Eurostat 2016a)
CO_2 emissions (indirect)	$kgCO_2/kWh$	0.396 (European average)	(EEA 2016)
CO_2 emissions cost	€/ton mid-2008	5	(Koch et al. 2014)
	€/ton mid-2013	30	

As for the EOL stage, it has to be noted that suspension arms generally are not dismantled since are not valuable reselling parts. For this reason they are shredded and metals are separated for further recycling. The main costs are calculated taking into account electricity consumption for shredding and post-shredding treatments (Table 25); labour cost is considered negligible since all these processes are mechanized treatments, while income from recyclable materials is not included due to the high variability of its price. Electricity consumption values were retrieved from measures of an Italian plant.

Table 25 Data inventory EOL stage suspension arm case study

Data	Unit	Value	Source
Electricity consumption for ferrous metal treatment	kWh/ton	40	Primary data
Electricity consumption for non-ferrous metal treatment	kWh/ton	25	Primary data
Electricity consumption for ASR treatment	kWh/ton	7	Primary data
ASR disposal cost	€/ton	100	Primary data
Electricity price (2016)	€/kWh	0.12 (European average)	(Eurostat 2016a)

4.7.3. Interpretation, Reporting and Critical Review

When the average cost reached in mid-2013 is assumed, the CO_2 cost was found negligible if compared with other cost; however its contribution is evident when the price referred to the mid-2008 is applied (Table 26).

Table 26 LCC results suspension arm case study ($CO_{2\,2013}$ and $CO_{2\,2008}$ are CO_2 costs referred to mid-2013 and mid-2008 EU emissions trading system periods respectively)

	Ref. $CO_{2\,2013}$		Light $CO_{2\,2013}$		Ref. $CO_{2\,2008}$		Light $CO_{2\,2008}$	
Materials	10.68	47.0%	23.92	57.3%	10.68	47.0%	23.92	57.3%
Manufacturing	5.76	25.4%	14.87	35.6%	5.76	25.4%	14.87	35.6%
Use	6.15	27.1%	2.77	6.6%	6.15	27.1%	2.77	6.6%
CO_2	0.10	0.4%	0.05	0.1%	0.61	2.7%	0.27	0.7%
EOL	0.02	0.1%	0.14	0.3%	0.02	0.1%	0.14	0.3%
Total	€22.71		€41.74		€22.71		€41.74	

No break-even point is reached within the life span (150,000 km). The materials, especially composite, and the manufacturing, in particular the labour cost, are the most important contributions. Indeed, the use of composites in the automotive sector is already too low to guarantee an optimization of processes and competitive cost if compared with traditional materials. Future scenarios can be assumed to evaluate which are the challenging values, in terms of material cost and processes parameter, to make the lightweight solution preferable or even comparable to the reference one. Forecast in terms of composite price and cycle time values for their manufacturing can be found (Heuss et al. 2012); in particular a moderate scenario can be assumed where composite cost and cycle decrease by 30% and 35% respectively; whereas an optimistic scenario foresees a reduction of 55% and 60% for the first and the second (Table 27).

Table 27 Moderate and optimum scenarios for the lightweight solution (Heuss et al. 2012)

	Light	Light mod.	Light opt.
Composite cost	20 €/kg	13 €/kg	9 €/kg
Cycle time	0.083 h/piece	0.05 h/piece	0.033 h/piece

By assuming these values, the LCC results for the lightweight solution change considerably reducing the difference between lightweight and reference solutions (Figure 22), moreover the optimistic scenario makes the lightweight solution even better than the reference.

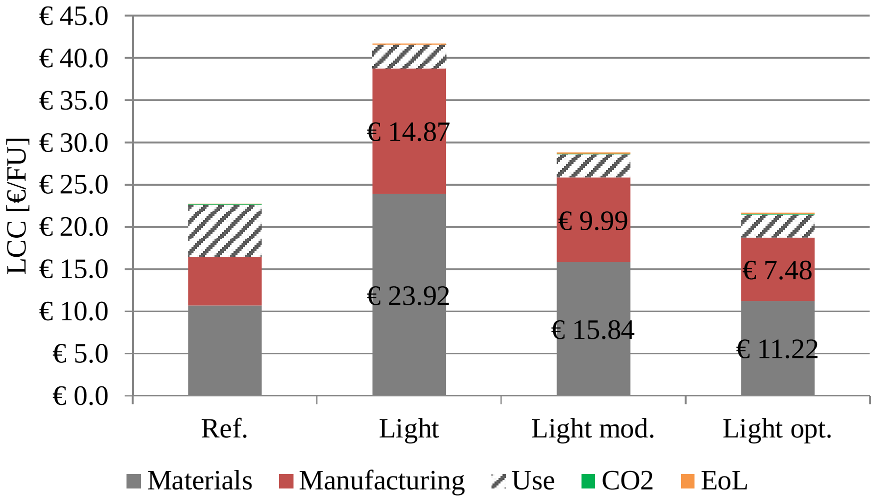
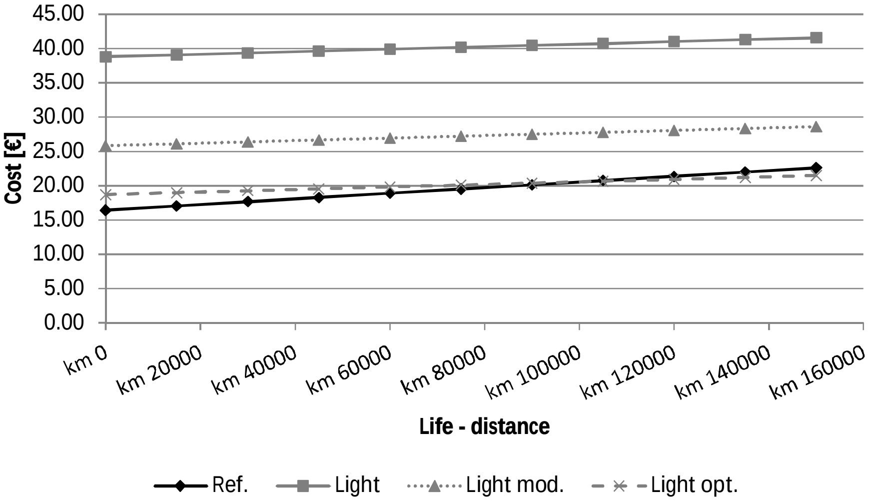


Figure 22 LCC results considering future scenario in the composite manufacturing

The breakeven analysis is used to evaluate the convenience of a solution by identifying at which vehicle's life distance the lightweight solution could give economic benefit if compared to the reference one. At the beginning of life-distance (kilometre 0) the cost includes materials and manufacturing, then the use stage cost increases with the distance until the assumed life span (150,000 km). At this point the EOL cost is summed.

The outcomes from the breakeven analysis are reported in Figure 23. The high production cost of the lightweight solution does not allow to reach a break-even point with the reference solution within the life span thus suggesting that there is not life cycle cost convenience from this solution. Only assuming the optimistic scenario the innovative solution crosses the standard one at 103,500 km. The analysis is carried out also considering use stage discounting (5%); in this case the break-even point is delayed at around 121,600 km.



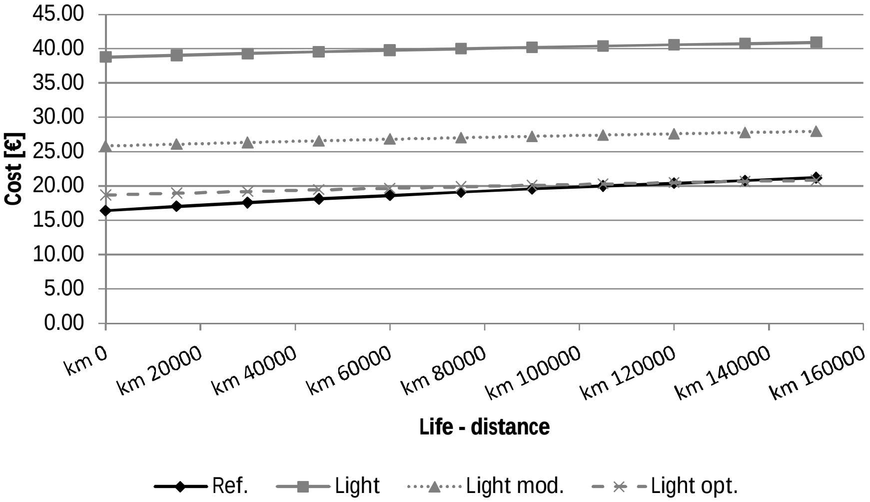


Figure 23 Breakeven analysis for the economic convenience: without discounting (upper), with discounting (lower)

It can be assumed that the suspension arm solutions could be feasible for different vehicle types (e.g. ICE and EV) since the design is not affected by the different vehicle propulsion systems in a considerable way. Therefore, the LCC was carried out considering two different use stage modelling: internal combustion engine (ICE) and electric (EV) and the results are shown in Figure 24. In the case of the ICE vehicle the use stage was modelled according to the mathematical equation described in Annex A; in particular assuming a Golf VI (diesel, Euro 6). As it can be observed, in both cases the increase in the production stage cost is not balanced by the cost reduction during the use stage, and the difference between reference solution life cycle cost and the lightweight one is slightly in favour of the ICE vehicle case, thus suggesting that overall only improving manufacturing processes, for example by reducing the cycle time, and reducing composite cost the lightweight solution could be beneficial from an economic point of view.

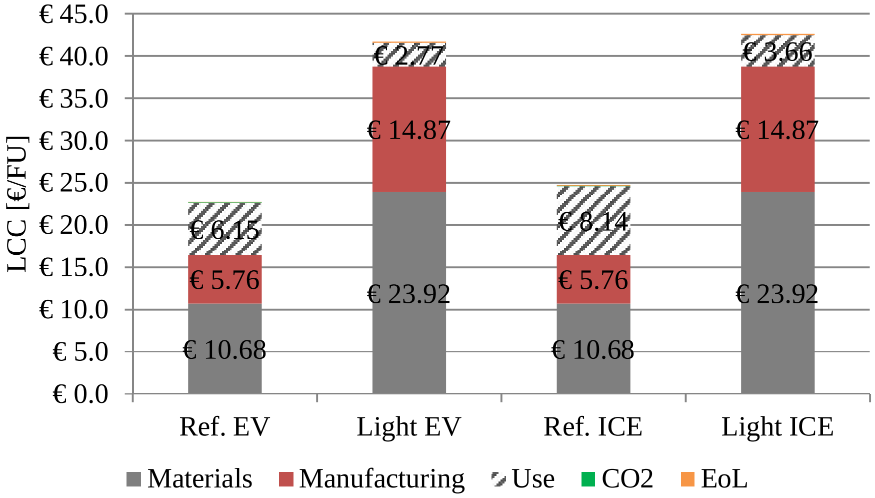


Figure 24 Lightweighting cost for different vehicle propulsion system

5. Social Life Cycle Assessment: a conceptual map for the goal and scope setting

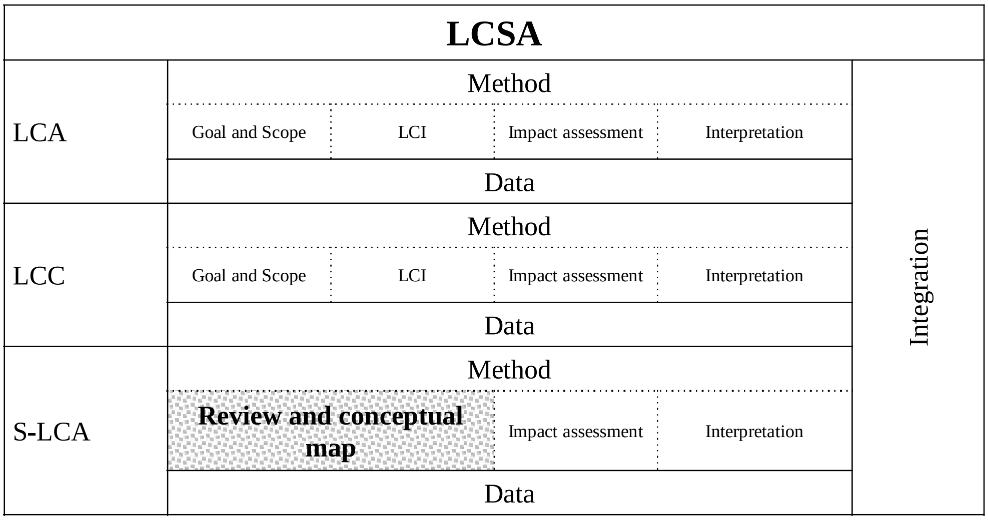


Figure 25 Scheme of research contributions to LCSA methodology: a conceptual map for a conceptual map for the S-LCA goal and scope setting

Among the life cycle-based methodologies, Social Life Cycle Assessment (S-LCA) is the youngest technique of analysis; it is a methodology aimed to assess the potential social and socio-economic impacts of products/services throughout their life cycle (UNEP/SETAC 2009).

Due to its recent launch there are much rooms for progress in the theoretical foundations of social impact assessment, functional unit, system boundaries convergence, indicators selection, among others (Mathe 2014). Despite an increasing number of scientific articles dealing with S-LCA applications during the last year it seems we are still far from solving these aspects.

This research would contribute by critically reviewing and questioning the most important elements affecting the goal and scope and inventory phase of S-LCA, with a focus on the automotive sector, with the ultimate goal of developing a structured approach to guide practitioners in the application of S-LCA, but also in the LCSA development (Figure 25).

This is achieved by (1) a critical review, whose results are shown and analysed in detail (cfr. § 5.1), (2) development of a conceptual map covering the goal and scope and inventory phase (cfr. § 5.2) , (3) discussion of automotive case studies and the corporate-related documents according to the conceptual map nodes to identify which aspects are already covered by the literature and which ones need further research (cfr. § 5.3).

5.1. S-LCA methodology overview and applications review

S-LCA developments and applications have been growing during the last years, both as a stand-alone methodology and within a more comprehensive life cycle-based sustainability assessment (hereinafter Life Cycle Sustainability Assessment – LCSA). However, from the methodology point of view, despite the initiatives at international and national level, S-LCA still presents many open issues which need further progress for the full operationalization of the methodology.

Indeed, it is generally recognized that selection of indicators (and inventory analysis), data availability and impact assessment methods are the most crucial issues for S-LCA, as well as for LCSA. Most of the scientific articles published so far have addressed the applicability of S-LCA, focusing on selecting and quantifying suitable and relevant indicators for the case study at hand, and only recently the developments in the area of impact pathway are increasing in number and relevance (Dreyer et al. 2005; Weidema 2006; Jørgensen et al. 2009; Parent et al. 2010; Reitinger et al. 2011; Feschet et al. 2012; Macombe 2014; Neugebauer et al. 2014; Bocoum et al. 2015).

However, a critical analysis of how to set a S-LCA study, in particular the goal and scope and inventory phase, is missing: practitioners rely on the procedure described within the UNEP/SETAC guidelines (UNEP/SETAC 2009), but do not question some key aspects that make the analysis a challenge, such as functional unit and system boundary definition, the scope of the assessment (company vs. product), just to mention some. Moreover, the lack of comprehensive and robust databases and the different type of social indicators (i.e. quantitative and qualitative), contribute to make the inventory phase a critical step.

A critical review has been carried out (cfr. § Chapter 2); its results are described in the following paragraphs and are discussed in relation to the elements affecting the S-LCA applications, in particular the goal and scope and inventory phases (Table 28).

Table 28 Sum up of the elements affecting the goal and scope and inventory phases of S-LCA applications stemmed from the review.

Elements affecting S-LCA applications (application-independent)	• Perspective
	• S-LCA as stand-alone methodology or within LCSA
	• Selection and prioritization of indicators
	• Functional unit
	• System boundaries
	• Background, foreground unit processes
	• Data sources, quality and geographic level

5.1.1. Perspective

The term “perspective” is used to indicate the angle from which the analysis is carried out. As such, it includes also the concept of “level of concern”, i.e. who should care about the consequences of a decision/action (Macombe et al. 2013). This concept stands out as an important aspect for better defining the scope of the analysis and the identification of the affected stakeholders. Three levels of concern are identified – company, regional, state – and they represent three different levels of decision-making whose different and potentially competing concerns may be regarded as aspects of assessing sustainable development of a project (Elghali et al. 2007). Moreover, within the same application different level of concerns can be identified according to the scope of the analysis. For example, in the case of a waste management system, if a company level of concern is considered, the evaluation of the social consequences of placing a new plant in a given area are at the core of the analysis. On the other hand, if a regional or state level of concern is relevant, the analysis should investigate the social consequences of the waste management system on the population and other stakeholders. However, only one of the reviewed paper deals with this aspect in a clear way, by relating the level of concern with the stakeholder groups identification (Macombe et al. 2013). In the other cases it seems that a super partes perspective is adopted (Umair et al. 2015). As guidance, the UNEP/SETAC guidelines provide a list of questions that need to be answered in the goal and scope phase of the study: Why is an S-LCA being conducted? What is the intended use? Who will use the results? What do we want to assess? (UNEP/SETAC 2009). However, it seems that these aspects are usually not dealt with in details, or at least evidence is not given in the published literature.

5.1.2. Social LCA: a stand-alone analysis or within a Life Cycle Sustainability Assessment

In most of the paper analysed the S-LCA is conducted as a stand-alone methodology and according to the UNEP/SETAC guidelines (UNEP/SETAC 2009).

Overall, the review points out that those works in which S-LCA was applied as a stand-alone analysis or within LCSA differ in three main aspects: definition of functional unit (cfr §5.1.3) and system boundaries, due to the need of ensuring consistency among the life cycle-based methodologies applied in the framework, and number of indicators (Schau et al. 2012; Traverso et al. 2012a; Martínez-Blanco et al. 2014).

As far as the indicators are concerned, the management and integration of a large amount of indicators characterised by a high heterogeneity is often mentioned as a key issue (Busset et al. 2014). The need of reducing and simplifying the number of indicators is particularly discussed in the LCSA context (Neugebauer et al. 2015) and more efforts are applied for selecting them, so as to ease the interpretation phase of the LCSA assessment and the communication of the results (Finkbeiner et al. 2010; Traverso et al. 2012b). This is particularly true for the social part since the number and the heterogeneity of the indicators still need further selection or aggregation procedures.

5.1.3. Functional unit

One of the most discussed aspect in the analysed papers is the use of functional unit, in particular two main challenges are claimed: the first is how to link social indicators to the functional unit (Parent et al. 2010; Zamagni et al. 2011; Norris 2013; Wu et al. 2014;

Martínez-Blanco et al. 2015); whereas the second concerns the transferability of social inventory information at organisational level (company behaviour information) to the product system (Zamagni et al. 2011).

Overall, most of the S-LCA studies define the functional unit (Petti et al. 2014), especially when S-LCA is carried out in the framework of a broader sustainability analysis, where the need of consistency with environmental LCA and Life Cycle Costing affects such choice. Nevertheless, beside the inherent quantitative nature of the functional unit, only few works specify the reference flow of their analysis, and many claim that the functional unit is identified only with the aim to better define the scope of the analysis (Foolmaun and Ramjeeawon 2012; Manik et al. 2013; Hosseinijou et al. 2013; Umair et al. 2015; Veldhuizen et al. 2015).

A few works, mainly those carried out within the LCSA framework, link social indicators to the functional unit (Busset et al. 2014; Martínez-Blanco et al. 2014) by means of applying different approaches. Indicator results can be scored according to their relative relevance based on international agreements and then aggregated using a weighting system (Martínez-Blanco et al. 2014). An additional data collection should be made in order to get information about activity variable values for each unit process analysed, since the current databases do not provide such information; moreover such values could be very different depending on the country (Martínez-Blanco et al. 2014). In other cases results are translated into a midpoint or endpoint indicator, as in the characterization models of LCA, and then related to a functional unit (Martínez-Blanco et al. 2014).

Another issue related to the use of the functional unit is the linkages of company behaviour information to the product system: this could be avoided by means of using the life cycle attribute assessment (Norris 2006), which carries information about the scope ("what percentage of my supply chain has attribute X?"). This is an alternative to the use of the functional unit, which does not imply, as pointed out by Norris (2013), that a functional unit is not necessary but simply, that the functional unit "might not be used as a way to report about" (Norris 2013, pp. 3).

However in most of the case studies this step is not performed and results are presented without a direct mathematical link to the functional unit (Franze and Ciroth 2011; Ekener-Petersen and Finnveden 2013; Macombe et al. 2013), or even kept at company level (Dreyer et al. 2010).

5.1.4.System boundaries

Including or not a specific unit process or flow in the analysis could depend on several factors such as the scope of the analysis, the relevance of the process and also the product system scheme (Dreyer et al. 2005). According to the UNEP/SETAC guidelines, system boundaries should not be crossed by 'product flows' (economic flow) but only by elementary flows, similarly to LCA. In addition to that, when S-LCA is performed within the LCSA framework, system boundaries need to show congruence among the different methodologies, i.e., they should include all unit processes with a meaningful impact on one of the three sustainability dimensions.

The concepts and set of rules used to describe the product system and the boundaries are not clearly explained in S-LCA applications (Lagarde and Macombe 2013).

According to (Foolmaun and Ramjeeawon 2012) and to the reviewed works, two different approaches to system boundaries definition can be seen: on the one hand the inclusion of only those parts of the life cycle which are directly influenced by the company performing the assessment, and on the other hand the inclusion of the entire life cycle, excluding the processes which can be considered non influential for the overall conclusions of the study. Most of the studies focus on those phases which are perceived more relevant and for which more specific data can be collected. For example those works concerning fuel and biofuel production include only feedstock production, processing steps and transport to pump and exclude the use stage (Blom and Solmar 2009; Manik et al. 2013; Ekener-Petersen et al. 2014); the study about automotive shredder residue includes only processes related to the treatment and management system, excluding production and use stages of the vehicle (Vermeulen et al. 2012).

Overall, it is not clear how to measure the relevance of a given process and only few works deal with this aspect, using for example Material Flow Analysis and assuming that the more important material flows are also those more responsible for socio-economic impacts, since more stakeholders are expected to be involved (Hosseinijou et al. 2013).

Moreover, it is claimed that when the product under evaluation interacts and/or has linkages (i.e. economic transactions and relationships) with other production chains, then alternative approach to represent product system and system boundaries could be needed, such as the systematic competitive model, supported by cut-off criterion guiding the system boundaries definition (Lagarde and Macombe 2013). In this case including or not a specific process, and the related organization, mostly depends on the socio-economic effect that a change in the product life cycle would produce.

5.1.5. Indicators selection and development

As far as indicators are concerned, they emerge as a challenging issue for two main reasons: i) there is not a clear distinction between impact indicators and inventory indicators (Neugebauer et al. 2014); ii) a robust approach for indicators selection is seldom discussed and reported in a transparent way.

The first aspect refers to the positioning of a given indicator along the impact pathway. For the time being a different approach in the indicators handling can be seen in Type I and Type II S-LCA. According to the S-LCA guidelines Type I and Type II differ in the different position of the collected data and results along the impact pathway (performance vs. impact) (Parent et al. 2010; Garrido et al. 2016).

Practitioners who rely on the first method (Type I) to develop the life cycle inventory phase, adopt the stakeholder-subcategories-indicators structure, starting from the inventory indicators proposed by the methodological sheet and until the evaluation of their performance (Garrido 2016). Whereas for the Type II a more heterogeneous scene can be seen; the main focus is on the identification of pathways (Norris 2006; Weidema 2006; Jørgensen et al. 2009; Feschet et al. 2012; Macombe 2014; Bocoum et al. 2015), while inventory data, which indeed are the variables computed by pathway calculations, are rarely highlighted or the data collection is seldom discussed and illustrated through case studies. In addition, Neugebauer (2014) proposes two pathways from inventory indicators to impact indicators, according to the cause-effect-chain generally used in the LCA framework. Finally, other researches have proposed to include specific indicators (mid-point level) regarding socio-economic consequences into the LCA framework (Weidema 2006; Vermeulen et al. 2012; Blok et al. 2013). In fact, even if S-LCA is proposed for the assessment of socio-economic impacts of products, some authors suggested that the environmental LCA framework would better allow to gather some social aspects (Mancini et al. 2016).

The indicators selection is the second challenging issue. The relevance is often mentioned as the criterion for indicators selection but further insights on how it is evaluated are not provided. It is generally claimed that some indicators are considered relevant for the sector at hand according to literature review outcomes (Schau et al. 2012; Ekener-Petersen et al. 2014) or to the Social Hotspot Database (SHDB)[8] results (Ekener-Petersen et al. 2014). In some cases, indicators have been selected according to their capabilities to reflect both positive and negative social effects of the given case study (Baumann et al. 2013), but the rationale behind the choice of the single indicators is not provided. A second initiative exist regarding database devoted to social domain. It is called Product Social Impact Life Cycle Assessment (PSILCA)[9], however it is still quite recent therefore no works applying it can be found in literature by now.

Most of the studies from Type I rely on the indicators proposed in the UNEP/SETAC methodological sheets (UNEP/SETAC 2013), and approach them on the basis of data availability, while a few stress the need of introducing additional indicators or stakeholder groups specific for their case studies (Vinyes et al. 2012; Martínez-Blanco et al. 2014). However, in most of the cases the addition of other stakeholder groups (and related indicators) relies upon the author's perception of what matters, while a sound and reproducible approach is neither presented nor its relevance is discussed. On the other hand, those works which develop S-LCA by means of SHDB demonstrate to give less importance to indicator selection, despite the high number of proposed indicators (22 social themes) (Rugani et al. 2014). It can be argued that the availability of database leads to consider all proposed indicators without the need of selecting those appropriate for a given application.

Prioritization among indicators is often mentioned but it is not meant in contraposition with relevance: the relevance can be considered a selecting criterion for indicators which afterwards are ranked according to a priority scale (Neugebauer et al. 2015).

Prioritization is considered a necessary step to select clear social targets and to obtain manageable results (Beaulieu et al. 2014). Moreover an indicator hierarchy is considered fundamental for reducing the level of knowledge and deepening necessary to develop a sustainability analysis, especially in view of LCSA (Neugebauer et al. 2015). Different approaches are proposed to create scales of prioritization such as relevance, practicality and method robustness (Neugebauer et al. 2015); in a few cases also social issues severity and country level socio-economic relevance are used (Beaulieu et al. 2014).

In the debate on the relevance and selection of indicators, the concept of bottom-up and top-down approaches stands up. The first one refers to an approach to the analysis in which indicators are identified based on industry or stakeholder interests and/or data availability (Kruse et al. 2008), and mainly in the business context of the product

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[8] The Social Hotspot Database (SHDB) relies on the global IO model derived from the Global Trade Analysis Project (GTAP) by New Earth, it provides social risk information on 22 social themes and including 89 issues. It offers a relevant way to model product category supply chains by prioritizing hotspots based on worker hours and assessing the potential social impacts that may be significant in particular countries and for specific sectors within that supply chain (SHDB 2016).

[9] The PSILCA has been developed by GreenDelta, it uses a multi-regional input/output database called Eora. It includes 88 qualitative and quantitative indicators, mainly inspired by UNEP/SETAC Methodological Sheets, classified in 23 subcategories (topics) and 5 stakeholder groups (workers; value chain actors; society; local community; consumers) (Ciroth and Eisfeldt 2016)

manufacturers (Dreyer et al. 2005). This approach is usually adopted when S-LCA is conducted as a stand-alone methodology, according to the UNEP/SETAC guidelines; in many cases the starting point of the analysis is the identification of the stakeholder groups therefore the life cycle inventory phase is developed according to the stakeholder-subcategories-indicators structure (Foolmaun and Ramjeeawon 2012; Umair et al. 2015).

Stakeholder involvement is considered fundamental for the identification of the most significant social aspects in the case of product and context-specific analysis (Mathe 2014) and the use of participatory approaches is considered useful to implement this process (Mathe 2014; De Luca et al. 2015).

Different stakeholder involvement techniques are applied in literature (Foolmaun and Ramjeeawon 2012; Manik et al. 2013; Hosseinijou et al. 2013; Umair et al. 2015; Veldhuizen et al. 2015), among which multi-step surveys and questionnaire are those more frequently presented. Surveys could involve an initial selection of stakeholders followed by a selection of indicators (Veldhuizen et al. 2015), or could involve an initial selection of relevant life cycle stages followed by a specific questionnaire for indicators (Hosseinijou et al. 2013). Stakeholders are usually asked to select social issues stemmed from different sources and not specifically classified according to stakeholder groups (Veldhuizen et al. 2015) or are asked to answer concerning stakeholder categories and indicators of UNEP/SETAC (Foolmaun and Ramjeeawon 2012; Umair et al. 2015). Whereas the application of the materiality principle is particularly used in the industrial context where the significance for the organization is related to stakeholder assessments to identify the material aspects[10](Ford Motor Company 2013; Benoît Norris and Norris 2014; BMW GROUP Group 2014; Volkswagen 2014).

Nevertheless a common and structured approach cannot be found in S-LCA applications (Mathe 2014), and a proper evaluation of the different techniques applied is difficult since only a few cases describe questionnaires, groups and number of people involved in a detailed way (Foolmaun and Ramjeeawon 2012).

As far as the top-down approach is concerned, what is valuable to society is the starting point of the analysis, and thus statements and values stemmed from international conventions and guidelines are considered, together with end-point impact categories when available (Macombe et al. 2013; Baumann et al. 2013). Thus the use of a scoring scale based on a number of criteria (i.e. severity in term of relation to fundamental agreements) is the process used for indicators selection (Beaulieu et al. 2014; Neugebauer et al. 2015).

It is generally recognized that an analysis which would involve relevant impacts and indicators should be based on the integration of top-down (normative) approach and bottom-up approach (Kruse et al. 2008; Capitano et al. 2010; Mathe 2014). Identifying robust and reliable way to integrate both of them is an important task for further structuring S-LCA applications.

Overall, the principles which guide both indicators and stakeholders' adoption are not always expressed since data availability and resource constraints are the main drivers of the analysis.

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[10] Material Aspects are those that reflect the organization's significant economic, environmental and social impacts; or that substantively influence the assessments and decisions of stakeholders (Global Reporting Initiative 2015).

5.1.6. Data source, data quality, background and foreground processes

Data source and quality is an important theme in S-LCA as a great number of information, both quantitative and qualitative, is needed, and their availability and robustness is critical to the study results. The UNEP/SETAC methodological sheets propose examples of sources (i.e. report of international agencies, NGOs, web sites) where some information can be collected, nevertheless they do not expect to be exhaustive and often direct data collection is needed to get more representative and suitable data. Moreover the use of generic data seems to be a more thorny aspect in S-LCA than in LCA, because performances are more locally variable and dependent on companies' behaviours instead than on the technology system.

The quality of data can be evaluated, among others, according to a geographic scale (company, sector, country) (Martínez-Blanco et al. 2014). The company level represents the site-specific data that is considered more valuable but more difficult to collect, while the country level is the average information of a given country that is expected to be less valuable but easier to collect. Within a study it is possible to use different types of a data depending on the product system, and on the data quality requirements set for background or foreground processes: foreground would reflect those processes where site and product specific data are necessary, whereas background are those processes which can be depicted by means of more general data (van Haaster et al. 2013) (Table 29). In the S-LCA context the discerning factors between foreground and background processes, and related data requirements, are the relevance of the process(es) and the level of interest and influence (Martínez-Blanco et al. 2014).

Another element which seems to affect the quality of data is the nature of the product analysed, i.e., whether a specific product of a company/value chain is analysed or a generic one (Benoît Norris et al. 2012; Ekener-Petersen and Finnveden 2013). In the latter case country-scale data are used exclusively (Table 29). In addition to that, when the supply chain is characterized by a high complexity in term of high number of suppliers and market rules, the identification of a "country significance" for each life cycle stage is suggested (Ekener-Petersen and Finnveden 2013). For example, in the case of raw material extraction stage the "country significance" could help in ranking the countries according to their total activity in the given stage and then identify the most active groups of countries which could be taken into account for data collection (Ekener-Petersen and Finnveden 2013).

Table 29 Geographic scale of data, unit processes classification and product type (well-defined/undefined value chain)

	Data type	
	Well-defined value chain	Undefined value chain
Background	Sector-, country-level	Sector-, country-level
Foreground	Company-level	

Regarding data source and quality, it can be observed that in those works where a no case-specific study is developed, the Social Hotspot Database is used (Schau et al. 2012; Ekener-Petersen et al. 2014). The database provides country and sector-country specific social data based on the GTAP multi-regional IO table. The database is comprehensive in terms of coverage of geographic contexts and sectors (113 countries and 57 sectors), however it has a low granularity which does not allow to cover process-level or company-level data (Norris 2013). When case-specific studies are dealt with, a detailed data collection is carried out (Blom and Solmar 2009), even supported by surveys (Manik et al. 2013) to allow testing people perception and expectation, and even validate information from official reporting (Blom and Solmar 2009; Manik et al. 2013). In these cases also statistic data from national or regional agencies are used (e.g. UNICEF publication concerning child labour, Work Environment Authority report of a given country concerning number of accidents). These data, which have different representativeness level for a given time period, could stem from the same sources used by the database but in this case the practitioner manages and select raw data directly.

5.2. A conceptual map to guide practitioners

The main findings of the review, listed in Table 28 and described in the previous paragraphs, have been organized into a conceptual map (Figure 26) for guiding practitioners in setting goal and scope and inventory phase of S-LCA studies.

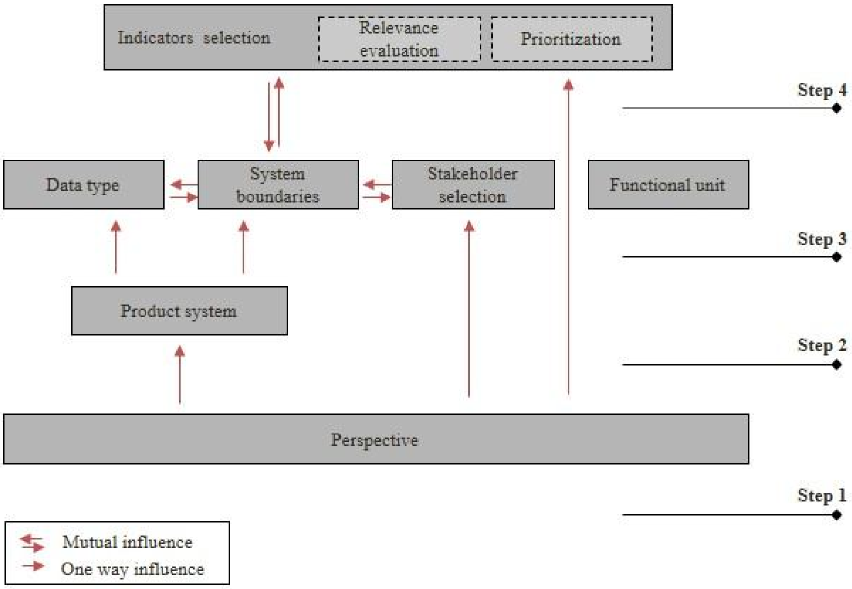

Figure 26 Conceptual map. It is organized along four steps, each including different nodes that can be faced also simultaneously. The single and double rows represent the influence among the nodes.

Therefore, all the methodological and practical issues have been sequentially placed by taking into account how they could influence the goal and scope and inventory phase of the S-LCA methodology. This sequence is not to be intended as a strict temporal series but as a suggestion for an orderly procedure consisting of several nodes. Each node represents a crucial point where a decision needs to be taken in order to carry out the analysis. The nodes are organized in four steps representing the procedure sequence; within each step, the nodes can be faced also simultaneously, depending on the application at hand. The single or double rows represent the relations between the nodes, i.e. the extent to which the nodes are affected each other's, and represent one-way relationship or mutual relationship, respectively.

The conceptual map is not meant to specifically target one of the S-LCA methods (Type I and Type II) as it covers aspects which are common to both. Indeed, according to the UNEP/SETAC guidelines and the scientific literature published so far, Type I and Type II can be considered as two different classes of impact assessment methods, which differ in two main aspects: i) the position of the collected data and results along the impact pathway (performance vs. impact); ii) the connection between indicators results and product system (Parent et al. 2010; Garrido et al. 2016). In this respect, the conceptual map applies to both, as the procedure to set for the S-LCA study requires to question how to properly set the goal and scope, and how to organize the inventory phase. The latter, is strongly affected by the type of impact assessment adopted: however, the issues of indicator selection, relevance and robustness are equally applicable.

It is generally recognized that S-LCA has been driven by a company's perspective mostly (Dreyer et al. 2005; Benoît Norris and Norris 2014) but this review has pointed out that arguments exist for applying it to different levels of analysis (Macombe et al. 2013). Thus, the *first step* of the conceptual map includes the node of perspective setting. The question that the practitioner should answer is: where, how and to whom the product system at hand is expected to produce effects? There are two main argumentations supporting this. The first is that LCA, and consequently S-LCA, are recognized as tool for decision support and any application of the methodology needs to be developed by considering who is the user of the study, which kind of information she/he is interested in and how the system analysed is intended to create an effect (Jørgensen et al. 2012). The second is related to the link between the perspective adopted and the stakeholders categories (Step 3): there could be contradicting interests between different stakeholder groups the S-LCA intends to consider, aspect that creates an unavoidable and challenging trade-off (Kruse et al. 2008). As a consequence, the limitation of the analysis to those stakeholders where effects are expected to be achieved could lead to more clear results.

The *second step* involves the product system description. This node regards both the approach used to define it and the product type (well-defined/undefined value chain). For the time being, there is no consensus on how to properly define the product system in the S-LCA context. However, a suggested procedure is to combine the technology-oriented approach, typical of LCA where the product system is made of several separated technological units positioned throughout the product life cycle, with the organization-oriented approach, where the product system consists of a number of individual companies dealing with industrial processes taking place throughout the product life cycle (Dreyer et al. 2005).

The product system definition directly influences the type of data (company-level, sector-level, country-level), in the way as described in Table 29, and the system boundaries identification which should reflect the double natures (technology- and organization-oriented) of the system under evaluation.

The *step three* involves four nodes. The system boundaries mostly regulate the extent of the analysis and the amount of required information, therefore this node concerns many relevant decisions. According to the double natures of the product system we identified two approaches for defining the boundaries of the analysis:

- *Effect-oriented approach,* which is related to the level of interest and influence;
- *Technology-oriented approach,* which is linked to the several physical units present in the product system.

However, the practitioner should be aware that the latter approach might not allow considering the effects on different stakeholders not directly connected to the product system. Moreover, it is not agreed how to evaluate the level of relevance, whether by means of a physical principle (physical flows) or economic one (added value) or even others, like working time contributions to the whole life cycle (Martínez-Blanco et al. 2014). On the other side, the adoption of the effect-oriented approach could not be in line with the life-cycle approach; thus, a low level of effect and influence characterizing some life cycle stages (i.e. use stage or EOL), should not hinder the development of a cradle-to-grave analysis.

Thus, the adoption of a double layer system boundaries is suggested to be adopted in S-LCA studies: the physic layer (technology-oriented approach) could allow to better define the production cycle and the entire life cycle stages; then the effect layer (effect-oriented approach) could ease the identification of the affected stakeholders and the related effects. An example of double layer representation is given in Figure 27. Indeed, the definition of a double layer could imply a higher level of complexity in the definition of what need to be included or not; in fact the identification of affected stakeholder groups could produce a Russian nesting doll situation in which more and more stakeholder groups are identified along the product life cycle stage and may be interlinked. However this is due to the inherent nature of social assessment and further insights upon its applicability could stemmed from case studies.

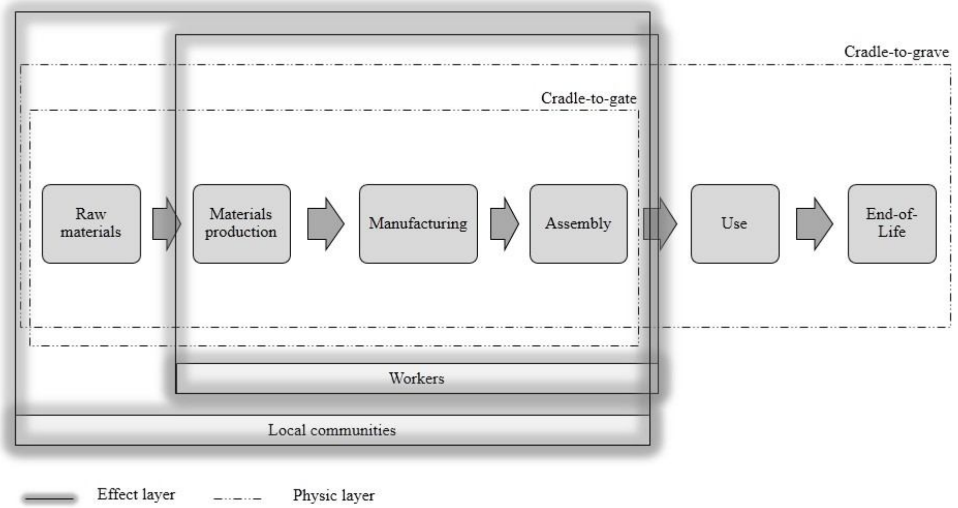

Figure 27 Double layer graphic representation of system boundaries. The example is provided for the cradle-to-gate analysis, but the same concept applies also to cradle-to-grave.

The system boundaries node has a mutual relationship with the stakeholders' node; this means that the identification of affected stakeholders, which in turn depends on the perspective, depends on the life cycle stages included in the analysis.

The *step four* of the conceptual map includes the node of indicators selection, in terms of evaluation of their relevance and prioritization. The evaluation of the relevance can be dealt with according to the two above mentioned top-down and bottom-up approaches, and a further prioritization could be necessary among the selected indicators, to obtain robust and manageable results.

5.3. Towards tailoring the conceptual map: building upon the automotive sector initiatives

The automotive sector was found to be more experienced in organization-oriented analysis (CSR and GRI) than product-based approach by means of S-LCA. Indeed, it was found out that only a few (14) applications of S-LCA, LCSA and more generally of social life cycle-based approaches are publically available.

However the number of environmental LCA studies, the interest in supply chain analysis and the recent initiatives about social assessment carried out by some companies of the sector are signals of an increasing interest about S-LCA applications in the sector.

The analysis of the sector-specific publications in the field of social sustainability - organization-oriented analysis and product-oriented S-LCA – currently do not allow to fully tailor the conceptual map to the sector, due to the limited sample, but it provides directions about some of the nodes of the conceptual map, in particular regarding system boundaries, indicators and stakeholders.

A small number of product-oriented S-LCA studies targeted to the automotive sector was found. They cover applications related to vehicle components/parts (Braithwaite 2001; Schau et al. 2012; Baumann et al. 2013; Karlewski 2016), alternative fuels (Blom and Solmar 2009; Manik et al. 2013; Macombe et al. 2013; Ekener-Petersen et al. 2014), materials for automotive parts (Zah et al. 2007; Alves et al. 2010; Reuter et al. 2014; Singh 2014), automotive shredder residue treatment (Vermeulen et al. 2012), and manufacturing technology (Chang et al. 2015).

The small number and the high heterogeneity of these studies do not provide clear trends in facing the conceptual map nodes (Table 30); indeed they confirm many of the criticalities already found in the other applications. For example the FU is generally defined (addressed) but results are presented without a direct link with it, whereas in some cases it is not even mentioned (not addressed); overall reasoning for that are not explicitly claimed (Table 30).

Regarding the product system and system boundaries definitions, the reviewed articles are found to mostly apply the technology oriented approach (Table 30). However, in the automotive sector applications adopting a double layer for the system boundaries appears preferable to face the important social issues which often are more in the background (supply chain) than in the foreground processes.

On the other hand the organization-oriented analysis points out the social issues of relevance for the sector and generally taken into account by the companies; this could guide the selection of indicators and stakeholders to be included.

As pointed out by the review of the sustainability reports (SRs) of the ten main car manufacturers in terms of European sales in the last years (ACEA 2015a), relevant stakeholders to be included – depending on the questions at hand - are: customers, dealers, employees, investors, suppliers (Tier I and beyond), local communities, governments at the national, state/provincial and local levels, nongovernmental organizations (NGOs), academia. In most of the articles only one stakeholder group, namely workers (Schau et al. 2012; Chang et al. 2015) is considered, whereas local community and society are included only to a less extent (Blom and Solmar 2009).

The materiality principle is well rooted into the sector, and it should be the guiding principle for defining indicators in any application.

According to the GRI approach, the starting point of the SRs is the materiality analysis to identify key issues and sustainability aspects that could represent both opportunities and risks to the company. The material aspects needs to be identified by considering “the impacts related to all of its activities, products, services, and relationships, regardless of whether these impacts occur within or outside the organization” (Global Reporting Initiative 2013). When the relevant topics are identified the organization has to prioritize them. According to the GRI guidelines, this can be done by means of the materiality matrix where the x-axis represents the significance of the organization’s economic, environmental and social impacts, and the y-axis the influence on stakeholder assessments and decisions (Global Reporting Initiative 2013).

As far as the social issues are concerned, within the context of SR it is possible to distinguish different classification of the material issues. Table 4 shows a list of the material issues which can be ascribed to social area, extrapolated and further elaborated from the materiality analysis of the companies (i.e. (BMW GROUP Group 2014; Volkswagen 2014)). Three main aspects can be noticed: i) in some cases the material issues are gathered according to categories internally defined by the Companies; ii) these categories can be ranked according to three keywords - society, workplace and supply chain; iii) a homogeneous terminology can be observed only for the workplace category. In addition to that a clear definition of them is not always present. As a consequence, an objective, transparent and robust identification of what matters in the sector becomes challenging. Moreover, with a few exception (PSA Peugeot Citroen 2014), it is not clear how the importance for external and internal stakeholder is evaluated and which are the scoring processes and the reference scale. In some case a scale between 0 and 100 is used to locate issues in the matrix (Daimler 2014), in another case a scoring process involving different weightings for internal and external groups is used (i.e. evaluation of the legitimacy and level of influence of stakeholders by issue category, likelihood of the impact) (PSA Peugeot Citroen 2014).

Table 30 Summary of conceptual map discussion according to the S-LCA studies in the automotive sector. The way each study has dealt with the conceptual map nodes is analysed and reported.

Reference	**Object**	**Perspective**	**Analysis framework**	**FU**	**Product system and System boundaries**	**Source of indicators**	**Selection of indicator**	**Stakeholders**	**Selection of stakeholders**	**Data source**	**Data quality**	**Analysis dimension**
(Alves et al. 2010)	Materials	company	not expressed	addressed	simplified system boundaries scheme based on technology oriented product system	not expressed	not expressed	local community	according to a subjective perception of the most affected	---	---	sustainability
(Baumann et al. 2013)	Automotive part	not expressed	not expressed	addressed	simplified system boundaries scheme based on technology oriented product system	eco-indicator 99 (DALY)	according to capability of measuring both negative and positive social effects of airbag system, also taking into account use stage	not expressed	---	literature	technology level	SLCA

Reference	**Object**	**Perspective**	**Analysis framework**	**FU**	**Product system and System boundaries**	**Source of indicators**	**Selection of indicator**	**Stakeholders**	**Selection of stakeholders**	**Data source**	**Data quality**	**Analysis dimension**
(Blom and Solmar 2009)	Biofuel	state	UNEP/SETAC	addressed	system boundaries scheme based on technology oriented product system	UNEP/SETAC methodological sheet	according to their general nature (those indicators which are considered too company-specific are disregarded)	employee, local community, society, company (consumers are excluded)	according to life cycle stages correlation	Internet, literature, journals, interviews	---	SLCA
(Braithwaite 2001)	Automotive part	designer	other	not addressed	not addressed	GRI	---	---	---	---	---	sustainability
(Chang et al. 2015)	Welding processes	company (industry)	UNEP/SETAC	addressed	not addressed	UNEP/SETAC methodological sheet	---	workers	---	literature	technology and state level	ELCA+SLCA
(Ekener-Petersen et al. 2014)	Fuels and biofuel	policy decision-maker (region, state)	UNEP/SETAC	not addressed	not addressed	SHDB	according to level of risk (SHDB terminology)	not expressed	---	SHDB	sector and state levels	SLCA

Reference	**Object**	**Perspective**	**Analysis framework**	**FU**	**Product system and System boundaries**	**Source of indicators**	**Selection of indicator**	**Stakeholders**	**Selection of stakeholders**	**Data source**	**Data quality**	**Analysis dimension**
(Karlewski 2016)	Automotive part	company, end consumer	UNEP/SETAC	addressed	---	PLAN, DO, CHECK, ACT indicators and other performance indicators	according to capability of describing management processes, and measuring social aspects	400 stakeholders from Daimler AG	---	survey	company	S-LCA
(Macombe et al. 2013)	Biofuel	company, region and state	not expressed	addressed	Three product systems for the different levels of concern, mostly organization oriented approach, and three system boundaries	eco-indicator 99, (Kim and Hur 2009), (Hofstetter and Norris, 2003), (Norris, 2006)	according to capability of measuring social impacts	workers, population (regional and state levels)	according to level of concern	---	regional, sector and state level (supposed)	S-LCA
(Manik et al. 2013)	Biofuel	policy decision-maker (region, state)	UNEP/SETAC	not used	simplified system boundaries scheme based on technology oriented product system	not expressed	not expressed	workers, local community, actors value chain, society	not expressed	survey	company, sector, country levels	S-LCA

Reference	**Object**	**Perspective**	**Analysis framework**	**FU**	**Product system and System boundaries**	**Source of indicators**	**Selection of indicator**	**Stakeholders**	**Selection of stakeholders**	**Data source**	**Data quality**	**Analysis dimension**
(Reuter et al. 2014)	Materials	designer	not expressed	not addressed	not addressed	SHDB	no selection	not expressed	---	SHDB	sector and state levels	S-LCA
(Schau et al. 2012)	Automotive part	remanufacturer and user perspectives	UNEP/SETAC	addressed	simplified system boundaries scheme based on technology oriented product system	SHDB	according to a subjective perception of which social risk, among SHDB ones, could be affected by the specific case study	workers	according to a subjective perception of the most affected	SHDB	sector and state levels	LCSA
(Singh 2014)	Materials	company	UNEP/SETAC	not addressed	not addressed	UNEP/SETAC methodological sheet	no selection	not expressed	---	---	---	SLCA

Reference	**Object**	**Perspective**	**Analysis framework**	**FU**	**Product system and System boundaries**	**Source of indicators**	**Selection of indicator**	**Stakeholders**	**Selection of stakeholders**	**Data source**	**Data quality**	**Analysis dimension**
(Vermeulen et al. 2012)	Automotive shredder residue	not expressed	other	addressed	system boundaries scheme based on technology oriented product system	eco-indicator 99	---	not expressed	---	literature	technology level	LCSA
(Zah et al. 2007)	Materials	designer	other (*Social Compatibility Analysis)	addressed	system boundaries scheme based on technology oriented product system	not expressed	not expressed	local community	according to a subjective perception of the most affected	---	---	sustainability

Table 31 Synthesis of the social material issues of the automotive sector stemmed from the materiality analysis of the corporate-related documents (*category defined by the Company in the SR)

Category*	Material issues	Source
Societal	Sponsorship and philanthropy	(PSA Peugeot Citroen 2014)
	Responsible marketing	
	Management of customers' personal data	
	Socially responsible mobility	
	Involvement in host communities	
Work forced related	Human rights and union rights	
	Diversity and equal opportunity	
	Attracting, developing and retaining talent	
	Health and safety at work and working conditions	
	Social dialogue and responsible management of jobs and skills	
No categories	Environmental and social standards in the supply chain	(BMW GROUP Group 2014)
	Anti-corruption/compliance	
	Product safety	
	Human rights	
	Occupational health and safety	
	Demographic change	
	Life balance	
	Further education and training	
	Diversity	
	Donation/sponsorship	
Society	Community engagement	(FIAT 2013)
	Commercial partner engagement	
	Human rights in the value chain	
	Ethics in business relation	
	Occupational health and safety	
	Customer satisfaction	
	Responsible management and development of employee	
	Diversity and equal opportunity for employee	
	Labour unions engagement	
No categories	Product safety	(GM 2014)
	Employee relations	
	Human rights	
	Employee equal opportunity and diversity	
	Local community	
People	Attractiveness as an employer	(Volkswagen 2014)
	Training	
	Participation (equal remuneration, labour relations)	
	Health	
	Diversity and equality	
	Corporate responsibility (indirect economic impacts, local communities, indigenous rights)	

Table 31 (bis) Synthesis of the social material issues of the automotive sector stemmed from the materiality analysis of the corporate-related documents (*category defined by the Company in the SR)

Category*	**Material issues**	**Source**
Social responsibility	Support of social sustainability initiative	(Daimler 2014)
	Regional commitment at our locations	
	Cross-regional commitment for social issues	
	Support of voluntary employee commitment	
	Commitment through our foundation efforts	
	Company-initiated projects	
Ethical responsibility	Human rights	
	Data protection	
	Compliance	
	Integrity	
Employee responsibility	Employer attractiveness	
	Training and continuing education	
	Occupational health and safety	
	Generation management	
	Co-determination	
	Diversity management	
Governance	Human rights strategy	(Ford Motor Company 2013)
	Ethical business practices	
Supply chain sustainability	Human rights in the supply chain	
	Sustainable raw materials	
	Identifying and managing sustainability-related supply chain risks	
Workplace	Workplace health and safety	
	Employee morale and teamwork	
	Employee labour practices /decent work	
	Diversity/equal opportunity	
Community engagement	Community engagement	
	Community impacts and contributions	

In some of the reviewed SRs the progress, priorities and goal related to the material issues are described in a qualitative way (GM 2014; Ford Motor Company 2013), but a lack of specific and harmonized indicators able to measure them is highlighted. Even if some SRs show a final list of social issues according to the GRI indicators (e.g. number of employees, average age, female, employee satisfaction index), nevertheless a direct correlation with material issues is not easy to be established.

The stakeholders' engagement is another common aspect in these SRs, according to the GRI guidelines. It includes identification and selection of stakeholder groups, approaches and frequency of engagement, key topics and concerns raised during the engagement process (Global Reporting Initiative 2013).

Along with some general description of different forms of engagement – such as quantitative consumer research studies, employee focus groups, congressional testimony, blogs, community meetings (GM 2014), direct contact, philanthropic programs, plant visits, endowed courses, events, assistance via foundations, website (NISSAN Motor Corporation 2014) – there are some SRs where these approached are detailed for each stakeholder group as well as the number of people involved (Ford Motor Company 2013).

In conclusion to make the materiality principle and stakeholder engagement the guiding principles of the indicators selection, practitioners have to clearly state in the study how the materiality is defined, and discuss it also considering the level of influence in addressing the social aspects.

6. Life Cycle Sustainability Assessment: integrating results by means of Multi-Criteria Decision Analysis

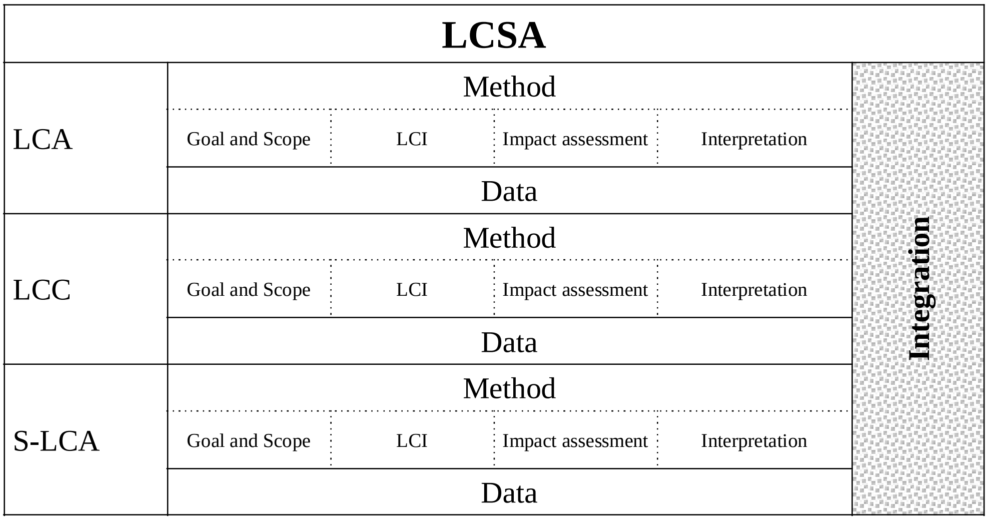

Figure 28 Scheme of research contributions to LCSA methodology: integrating LCSA results by means of Multi-Criteria Decision Analysis

There is a need to consider environmental, economic and social consequences originated by a certain design solution, as a consequence of material choices, manufacturing steps, the manner in which the product could be used and treated at its end.

Life Cycle Sustainability Assessment (LCSA) is a candidate for supporting the early design phase as far as it is able to quantitative compare different product concepts and to provide insights about room of improvement, such as alternative materials or processes, also describing trade-off transparently.

Within the UNEP/SETAC initiative framework and the recent studies, many research directions arose concerning LCSA implementation. Some of them mainly result from the S-LCA open issues (described in Chapter 5), however other elements typically regard the LCSA and are presented in the following paragraphs. In particular the issue of results integration and interpretation, as well as stakeholder engagement, are considered essential to be explored.

During the present research the integration of environmental, economic and social results has been tackled (Figure 28). The main findings regard: (1) review of LCSA studies, focusing on methods for combining and presenting results, in this sense the Multi-criteria decision analysis is treated with the aim of identifying its role in the LCSA (cfr. § 6.1), (2) description of the TOPSIS method, combined with the intuitionistic fuzzy, as suitable MCDA method to rank alternatives according to a set of sustainability criteria (cfr. § 6.2), (3) selection of a set of sustainability indicators and the results of a survey for their prioritization (cfr. § 6.3), (4) calculation of criteria weights to be used for the results integration (cfr. § 6.4).

6.1. LCSA overview

To give a guide on how to carry out a LCSA through the combined application of the existing environmental Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA), the UNEP/SETAC Life Cycle Initiative published LCSA guidelines (UNEP/SETAC 2011). The LCSA is mentioned as overarching methodology builds upon the ISO 14040:2006 and consequently comprising the four phases:

1. LCSA goal and scope;
2. LCSA inventory;
3. Impact assessment;
4. LCSA interpretation.

The LCSA of a product/process is carried out through a contemporary and complementary implementation of the three above-mentioned methodologies. However, beside a common framework, the three methodologies inherently present different features asking for specific considerations when facing the four phases within a complete sustainability assessment. Moreover the levels of maturity and experience is different for the three sustainability methodologies (LCA, LCC and S-LCA). The state of the art of the three methodologies has been presented and discussed in the previous paragraph taking into account the given recommendations for their further developments also in line with the expectations from the automotive sector.

As for the LCSA, the (UNEP/SETAC 2011) guidelines claims the following recommendations:

- Common goal and scope;
- Common product functional unit;
- *“System boundary should contains all unit processes relevant for at least one of the techniques”*;
- *“It is recommended that all impact categories that are relevant across the life cycle of a product are selected. These should follow the perspectives provided by each of the three techniques and consider the stakeholder views when defining the impact categories”*;
- *“It is recommended that data is collected at the unit process and organizational level”*; moreover all types of data (quantitative, qualitative and semi-quantitative; site-specific and generic data) need to be collected along the life cycle;

- *"It is recommended that the classification and characterization steps are implemented as the minimum and mandatory steps according to ISO 14040 (2006) and ISO 14044 (2006) but also taking into account the specific nature of each analysis (e.g. LCC does not have impact assessment)"*; *"…a combined framework for impact assessment based on the individual S-LCA, LCC and (environmental) LCA frameworks is recommended"*, while *"…any aggregation and weighting of results of the three techniques used are not recommended because of the early stage of LCSA research and implementation and because the individual aims of each of the techniques applied are not directly comparable to the other"*;
- *"It is recommended that the results are read in a combined fashion based on the goal and scope definition".*

In addition to the overarching challenges, more specific research directions arose from the recent LCSA studies. The most frequently cited is to develop practical LCSA case studies as a way to foster the methodology (Zamagni et al. 2013).

When putting into practice LCSA, it is evident that some challenges concern the methodology itself while others regard the level of maturity of the single technique and their intrinsic features; therefore further effort has to be devoted to the development of these methodologies. As an example, the recent applications and research about the S-LCA methodology show that some concepts typical of LCA do not completely fix with the intrinsic feature of a social analysis (e.g. functional unit and a product-level assessment) (Martínez-Blanco et al. 2014).

In the Sustainability Science, the LCSA aim *"is to promote social learning and mutual feedback (learning through doing and doing through learning) leading to coproduction of knowledge with other stakeholder groups, such as businesses, politicians and society in a common process of problem identification and resolution"* (Sala et al. 2013).

Overall, comprehensive sustainability assessments are discussed for their big challenge of merging goal and scope of different and, probably, contradicting dimensions (environment, society and economy) and, as a consequence, not delivering simple answers. It is evident that when complex problems such as whether to implement a new technology or produce a new product are faced, then simple answers can hardly be found (Keller et al. 2015). To be more precise, simple information and findings can be obtained but with the risk of ignoring important aspects. As a consequence, a comprehensive sustainability assessment needs to be developed in an adequately complex strategic decision process and, in this context, a proper goal and scope definition plays a key role.

According to the UNEP/SETAC (2011), the LCSA goal and scope phase describes the purpose, delimitation and the target audience of the study and includes the definition of functional unit, system boundaries, impact categories and allocation methods, according to the ISO 14040-44:2006 definition. However, when a combined approach of LCA, LCC and S-LCA is undertaken it is important to consider the different aims and features that such techniques inherently have.

Proposals to define goal and scope in a structured and appropriate way are questioned by some authors (Hu et al. 2013; Stefanova et al. 2014). The first author (Hu et al. 2013) proposes three operational steps: i) broad system definition to identify the problems and the main interrelations (synergies, conflicts, trade-offs, etc.) between the objects, processes, stakeholders and between the environmental, economic, social domains; ii) making scenarios; iii) defining sub-questions for individual tools (i.e. LCA, LCC). These steps are then carried out to compare concrete recycling solutions. Following these argumentations, (Stefanova et al. 2014) suggests three alternative main building blocks: i) macro-goal definition, when the ultimate goals and the macro-level problems are defined; ii) mapping the technology system to identify a number of possible scenarios through which the technology system can be implemented; iii) structuring the context representation where the system is embedded to clearly identify the involved stakeholders and the relevant mechanisms (i.e. socio-economic, cultural, normative) that need to be modelled in the LCSA study. Such steps are then tested with an on-going study about a new technology for the production of high purity hydrogen from biomass.

The UNEP/SETAC (2011) recommends that the functional unit describes both the technical utility of the product and the product's social utility. Overall, the literature concerning S-LCA applications as a stand-alone technique shows that there isn't a clear and common vision on how the functional unit can be used (Zanchi et al. 2016). This is mainly due to the inability to link the S-LCA assessment to the functional unit due to the different nature of relationship between technologies, industrial processes and social impacts, and the nature of indicators (i.e. qualitative) (Hu et al. 2013; Martínez-Blanco et al. 2014). Most of the LCSA studies define functional unit as a fundamental element for the LCA and LCC development and comparison between alternatives (Vinyes et al. 2012; Bachmann 2012; Hu et al. 2013) but do not address the link of social data to the functional unit. This issue is addressed in paragraph 5.1.3.

Ideally, LCSA should consider equivalent system boundaries for the environmental, economic and social assessment however many authors demonstrate that this can be hardly done; LCA and S-LCA could refer to a system which is defined in a different way (Lagarde and Macombe 2013; Zanchi et al. 2016), certain parts may fall under cut-off criteria regarding some sustainability aspects but not for others (Keller et al. 2015), moreover lack of comprehensive social databases limit, for the moment, the S-LCA development to the whole life cycle (Martínez-Blanco et al. 2014). This issue is addressed in paragraph 5.1.4.

In the LCA framework it is implicitly accepted a multi-stakeholder perspective which is automatically assumed and supported by the person who is carrying out the analysis; on the contrary, in the LCC context different perspectives come out (Hunkeler et al. 2008; Swarr et al. 2011), similarly to the S-LCA (cfr. § 5.1.1). As a consequence, how to deal with different perspectives and interests is another challenging issue for the LCSA.

The high number of indicators and the few experience, especially regarding social and socio-economic indicators, in the LCA area represent something which demands special efforts for the LCSA advancements (Kloepffer 2008; Finkbeiner et al. 2010; Zamagni et al. 2013). According to (Neugebauer et al. 2015) "*The bottleneck is not the lack of good indicators, but rather the lack of a clear indicator selection process*", therefore a Tiered approach is proposed as a transparent hierarchic order and guide for selecting indicators and so for directing data collection. Yet, data availability, especially social information need to be expanded during next years; currently two initiative exist regarding database devoted to social domain. The first is called the Social Hotspot Database (SHDB) (SHDB 2016) (cfr. § 5.1.5.), whereas the second is the PSILCA (Product Social Impact Life Cycle Assessment) database (Ciroth and Eisfeldt 2016) (cfr. § 5.1.5.). Some works applying SHDB can be found in literature (Schau et al. 2012; Martínez-Blanco et al. 2014), whereas the PSLICA is still quite recent.

Additionally, some authors claim the importance of extending the assessment to further impacts on environment, economy and society which are not yet robustly covered by LCA, LCC and S-LCA, to avoid the overlooking of important sustainability issues (Keller et al. 2015).

Apart from challenges with regard to indicators selection, LCSA has to deal with appropriate methods for results presentation. According to the overarching objective of avoiding compensation between the pillars (Kloepffer 2008), the most frequently mentioned challenges are the integration of results (Bachmann 2012; Atilgan and Azapagic 2016), the communication and interpretation of results (Finkbeiner et al. 2010; Traverso et al. 2012b).

According to (Keller et al. 2015), two general ways of integrating results can be observed from LCSA literature:

- Aggregation by weighting;
- Structured discussion of advantages, disadvantages and trade-offs.

Both are devoted to provide an overall picture and derive recommendations to decision makers; they present advantages and disadvantages and whether the first or the second group is the most appropriate mainly depends on the specific objective of the analysis and how results are intended to be used.

A transparent but comprehensive method for presenting results is important since non-experts are usually the target audience, and a single score or a graphical presentation of results is appreciated in those decision making situations when alternatives are compared (Traverso et al. 2012b).

A structured discussed, based on verbal argumentations and benchmarking tables, is promoted in those cases particularly complex where the subjectivity of value-based weighting should be avoided and information of both quantitative and qualitative indicators need to be exploited (Keller et al. 2015).

Weighting is seen as one option that is not recommended in every occasions but which is generally used in the decision making context (Finkbeiner et al. 2010). LCSA has to deal with weighting between indicators at different levels (i.e. impact vs. performance, mid-point vs. end-point): within each sustainability dimensions (LCA, LCC and S-LCA) and among the three dimensions. Two approaches are presented in literature: the Life Cycle Sustainability Triangle, which can be applied to weight any three dimensions; the Life Cycle Sustainability Dashboard, where a certain number of indicators are grouped into topics (i.e. a given social topic or the whole S-LCA). The dashboard, implemented in a software, manages the indicators values by comparing them to the best and worst scores obtained among the alternatives, then it provides results in terms of score between 0 and 1000 and according to a chromatic scale for each topic (Finkbeiner et al. 2010; Traverso et al. 2012b). The Life Cycle Sustainability Dashboard has been applied in several case studies, for comparing alternative remanufactured alternators design (Schau et al. 2012), for comparing three fertilizer alternatives (Martínez-Blanco et al. 2014), for comparing two geographic location for the assembly step of photovoltaic (PV) modules production (Traverso et al. 2012a). Also the method proposed by (Vinyes et al. 2012) relies on the comparison between scores of alternatives. It first calculates the contribution of each indicator with respect to the highest values gained among alternatives; then, assuming the same weight for each sustainability dimension, it calculates the sustainability factor for the three areas of sustainability. All the calculations are performed by taking into account the different nature of indicators in terms of positive or negative effects they represent (negative indicators are those that high values have a negative contribution to sustainability and positive indicators are those that have a positive contribution to sustainability), however the method allows to calculate the sustainability factors since quantitative indicators are used.

The Life Cycle Sustainability Triangle is used by (Onat et al. 2016a) to show how the rankings of alternatives is affected by the decision-makers' priorities (weights of criteria).

A verbal-argumentative discussion is proposed by (Keller et al. 2015). This approach comprises the following steps: selection of relevant scenarios and indicators; addition of suitable cross-disciplinary indicators different from the ones proposed by the LCA; compilation of overview tables; benchmarking; discussion. The main advantages attributed to this approach are: suitable in complex decision situations; to make trade-off transparent; feasible for both quantitative and qualitative indicators, and negative and positive indicators; not require value-based weighting.

Indeed, how to deal with value choices and subjectivity in the weighting step is a relevant aspect (Guinée 2016). Weighting is contested because not based on scientific facts, rather it is more built on normative judgments or relevance level perceived by an expert panel. For this reason it could lead to figures representative for a given time and geographic context. Moreover, it is claimed to not guarantee transparency, and thus limiting trade-off analysis, and to force an absolute judgments concerning a topic.

Overall, weighting process is well experienced in the Multi-Criteria Decision Analysis therefore interesting insights can be retrieved for the LCSAs; this topic is addressed in paragraph 6.1.1.

Double-counting and time-horizon are other challenging elements from a methodological point of view. The double-counting risk is originated when LCA, LCC and S-LCA account for the same effect; for example, CO_2 emissions effect could be assessed according to environmental (e.g. $kgCO_{2-eq}$) rather than economic point of view (e.g. €/kg CO_2). Yet, double-counting is not limited to the case of external costs included in LCC, but also it could arise when resource depletion is considered in the LCA and simultaneously included in LCC as resource cost (Bachmann 2012). Nevertheless, this topic seems to be rarely addressed in the LCSA literature (Bachmann 2012).

LCA and S-LCA usually do not account for the effects of time, whereas discount rate is sometimes applied in the LCC and this can affect results considerably (cfr. § 4.7). It is affirmed that reporting the temporal and spatial distribution of impacts allow highlighting the different generations affected, and this sense using different discounting and equity weighting schemes to aggregate results represents a challenging topic (Bachmann 2012). However, this aspect is seldom discussed so, until the LCSA approach matures, it is recommended that steady-state rather than dynamic approaches would be employed.

6.1.1.MCDA in the context of sustainability assessment

Multi-criteria decision analysis (MCDA) is widely used to solve decision-making problems and help to identify the best alternative/s when multiple criteria and alternatives are taken into account (Onat et al. 2016b).

Different types of MCDA methods exist, including Weighted Sum Method, Analytical Hierarchy Process, TOPSIS, VIKOR, ELECTRE, PROMETHEE, among others (Wang et al. 2009). A clear overview of them, in terms of advantages/disadvantages and sector, can be found in literature (Wang et al. 2009; Aruldoss et al. 2013). MCDA methods have been applied in many domains; in the automotive sector, they are particularly used in the material selection process (Jeya Girubha and Vinodh 2012), impact of reverse logistics practices (Haji Vahabzadeh et al. 2015), technologies for fuel cells as the power systems for vehicles (Sadeghzadeh and Salehi 2011), as well as to select the best fuel-based vehicles (Safaei Mohamadabadi et al. 2009).

MCDA methods have been extensively combined with the LCA, and recently they have become popular in the decision-making regarding sustainability of processes/products due to the multi-dimensionality of sustainability problems (Wang et al. 2009; Bachmann 2012; Atilgan and Azapagic 2016).

Yet, the use of MCDA to integrate the three aspects of sustainability – environment, economy and society – within the LCSA framework is analysed by some authors in different sectors (Halog and Manik 2011; Bachmann 2012; Onat et al. 2016b; Onat et al. 2016a; Atilgan and Azapagic 2016).

Atilgan and Azapagic (2016) applied the Weighted Sum Method to integrate twenty life cycle sustainability indicators to evaluate alternative electricity supply options in Turkey. A mixture of environmental LCA indicators (i.e. abiotic resource depletion, global warming potential, and acidification potential), economic indicators (i.e. levelized cost, capital cost) and social indicators concerning employees and workers safety are employed. First equal importance is assumed, followed by additional evaluations concerning results sensitivity to weights variations.

On the other hand, Onat et al. (2016a) developed a combined MCDA method to rank alternative vehicle technologies (i.e. internal combustion electric vehicle, hybrid electric vehicle, battery electric vehicle) utilizing TOPSIS and fuzzy set approaches. In this case macro-level indicators are used (e.g. GDP, total GHG emissions, water withdrawal), as representative for the economic, environmental and social area, and they are evaluated according to decision-makers’ judgments.

Besides the capability of combining different sustainability criteria and ranking alternatives, the integration of life cycle thinking methodologies (LCA, LCC, and S-LCA) and MCDA is thought a promising research area since could also enhance stakeholder involvement in LCSAs, as encouraged in the UNEP/SETAC guidelines. Therefore further work and practice would be needed in this sense.

6.1.2.Life Cycle Sustainability Assessment for the automotive sector

Few works exist about LCSA application in the automotive sector, to the best knowledge of the author. Some of them have been reviewed in Chapter 5 to give insights about social assessment settings (Schau et al. 2012; Vermeulen et al. 2012), others are hereby described. (Schau et al. 2012) describes sustainability assessment on remanufacturing alternators by comparing different designs and plants locations; social data have been retrieved from SHDB then results are summarized by means of the Life Cycle Sustainability Dashboard. Alternative vehicle propulsion systems are compared by means of LCSA in (Onat et al. 2016b; Onat et al. 2016a), sixteen macro-level sustainability indicators are used to compare seven vehicle types. LCSA is applied to highlight how the inclusion of economic and social dimensions can support the policy strategies development and how such tool can aid decision-making process and trade-off interpretation. In this case, results integration and interpretation are done by means of MCDA approach (TOPSIS method) which allows ranking alternatives and find out the most preferable one. Moreover, the Life Cycle Sustainability Triangle is applied to compare the best and the worst alternatives and to see how the decision-makers’ judgments can influence the ranking (Onat et al. 2016a). (Vermeulen et al. 2012) applies a set of seven sustainability indicators (energy intensity, material intensity, water consumption, land use, global warming, human toxicity, treatment cost) suitable for assessing and comparing alternative ASR treatment strategies from a sustainability point of view.

Although including the three pillar concept in the vehicle design is generally encouraged (Pallaro et al. 2015), there are no studies dealing with LCSA application as a supporting tool during component/vehicle design, with the exception of (Schau et al. 2012). This study claims that one of the most important obstacle encountered is the S-LCA maturity; in particular data accessibility and the use of suitable indicators need to be necessary developed and discussed taking in terms of the possibility of mapping and distinguishing social consequences behind alternative designs (i.e. materials, manufacturing technologies).

6.2. TOPSIS and intuitionistic fuzzy set to integrate results

In this research the application of the Multi-Criteria Decision Analysis (MCDA), the TOPSIS method specifically, is presented and discussed as a way to integrate LCA, LCC and S-LCA results.

Among the several MCDA method, TOPSIS was found to be one of the most popular especially in the engineering area (Velasquez and Hester 2013). Its advantages, in relation to other methods, can be retrieved from literature. First it is able to manage variables with different units of measure and so each type of criteria (Caterino et al. 2008). If compared to other methods, TOPSIS method does not consider the correlation of attributes; nevertheless it considers, together with the distance from the ideal positive alternative, also the distance from a negative-ideal option obtained combining the worst performances of alternatives in respect to the single criterion (Caterino et al. 2008). Its mathematical operations and data could be easily handled and programmed since the number of steps remains the same regardless of the number of criteria; moreover it does not require any decision maker intervention rather than the criteria weights. Finally, it is particularly suggested for those decision case with a low number of alternatives (Caterino et al. 2008; Velasquez and Hester 2013).

The TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method provides to obtain the ranking of alternative depending on their performances with reference to a set of criteria and the importance that such criteria have according to different kind of judgment. In general, a multi-criteria decision problem consists of determining the optimal alternative. A among a discrete set of *m* alternatives a_i, (i = 1, 2,…, m), which are evaluated with respect to a set of *n* criteria C_j, (j = 1, 2,…, n) formulated in a matrix format. The TOPSIS method is based on the following principle: *“the best alternative should have the shortest distance from the positive ideal solution in geometrical sense and the longest distance from the negative ideal solution”* (Wang et al. 2009). It is assumed that each criterion has a tendency of monotonically increasing or decreasing utility, so the preference order of the alternative is obtained on the basis of this relative distance to positive/negative ideal solutions.

The Intuitionistic Fuzzy Set (IFS) method, an extension of the concept of fuzzy sets, is applied in many systems to solve the problem of subjectivity and imprecision which unavoidably affect the human judgment on a group of criteria; for this reason fuzzy set theory is often proposed in combination with MCDA methods (Wang et al. 2009).

In this study the method proposed by (Onat et al. 2016a) is applied: expert judgments are used in determining the relevance of each of the 32 criteria presented in Annex C, the intuitionistic fuzzy set method is applied to deal with uncertainties of preferences and determine weights of criteria, then TOPSIS method is used to rank alternatives.

6.2.1.Step 1: Decision makers opinions

A set of k decision makers $d = \{1, 2, \dots, k\}$ evaluate the relevance of a set of n criteria j= $\{1, 2, \dots, n\}$, according to their experience, using linguistic terms linked with Intuitionistic Fuzzy Numbers (IFNs). Equal or different weights could be assumed for the decision makers.

This step has been developed by means of an online survey described in the following.

6.2.2.Step 2: Intuitionistic fuzzy set method

The steps used in the intuitionistic fuzzy set procedure are summarized as follows.

1. Determine the Intuitionistic Fuzzy (IF) decision matrix.

The decision makers opinion are translated into the IF decision matrix is $D = \left[s_{jd}\right]_{n\times k}$whose elements s_{jd} are the IFNs, linked to the dth decision maker assessment about the jth criteria. In this research a trapezoidal fuzzy number is applied; so the IFN can be defined as $\{(n_1, n_2, n_3, n_4 | n_1, n_2, n_3, n_4 \in R;\ n_1 \leq n_2 \leq\ n_3 \leq n_4)\}$, and respectively represent the smallest possible, most promising, largest possible values. It is considered preferable than the triangular fuzzy number as can encompass more uncertainty (Jeya Girubha and Vinodh 2012).

2. Construct the aggregated IF decision matrix.

The fuzzy rating of each jth criterion and kth decision maker need to be aggregated to $\hat{s}_j$ values expressed as $\hat{s}_j = \{\hat{s}_{j1};\ \hat{s}_{j2};\ \hat{s}_{j3};\ \hat{s}_{j4}\}$ calculated using the equations

$$\hat{s}_{j1} = \min\{s_{jd1}\} \tag{13}$$

$$\hat{s}_{j2} = \frac{1}{k}\sum s_{jd2} \tag{14}$$

$$\hat{s}_{j3} = \frac{1}{k}\sum s_{jd3} \tag{15}$$

$$\hat{s}_{j4} = \max\{s_{jd4}\} \tag{16}$$

In this research, the weights of decision makers were assumed to be equal.

3. Determine the Intuitionistic Fuzzy ideal solution.

The intuitionistic fuzzy negative ideal solution (IFNIS) ρ^- and the intuitionistic fuzzy positive ideal solution (IFPIS) ρ^+ are represented by IFNs. In this study it has been assumed that the first (ρ^-) is equal to the lowest level of relevance in the linguistic terms (very unimportant), whereas the second (ρ^+) corresponds to the highest level (very important).

4. Calculate distance measures.

The positive distance measure D_j^+ and the negative distance measure D_j^- are calculated by means of the equation:

$$D_j^+ = \left[\left(\hat{s}_{j1} - \rho^+\right)^2 + \left(\hat{s}_{j2} - \rho^+\right)^2 + \left(\hat{s}_{j3} - \rho^+\right)^2 + \left(\hat{s}_{j4} - \rho^+\right)^2\right]^{1/2} \quad (17)$$

$$D_j^- = \left[\left(\hat{s}_{j1} - \rho^-\right)^2 + \left(\hat{s}_{j2} - \rho^-\right)^2 + \left(\hat{s}_{j3} - \rho^-\right)^2 + \left(\hat{s}_{j4} - \rho^-\right)^2\right]^{1/2} \quad (18)$$

5. Determine the closeness coefficient value of each jth criterion by means of the equation.

$$\acute{C}_j = \frac{D_j^+}{D_j^- + D_j^+} \quad (19)$$

6. Calculate the weight of each jth criterion by means of the equation.

$$w_j = \frac{\acute{C}_j}{\sum_{j=1}^{n} \acute{C}_j} \quad (20)$$

thus determining the vector $W = [w_1, w_2, \dots, w_n]$ which is used in the TOPSIS method.

6.2.3. Step 3: TOPSIS method

The procedure of TOPSIS can be expressed in a series of steps described in the following.

1. Determine the decision matrix $[A]_{m\times n}$ where a discrete set of m alternatives is related to a finite set of n criteria. Each element a_{ij} of the matrix is the score (impact or performance) of the ith alternative corresponding to the jth criterion.
2. Calculate the normalized decision matrix $[R]_{m\times n}$ where the normalized values are calculated using the equation:

$$r_{ij} = \frac{a_{ij}}{\sqrt{\sum_{p=1}^{m} a_{pj}^2}} \quad (21)$$

This process converts the various criteria dimensions into non-dimensional criteria.

3. Calculate the weighted normalized decision matrix $[V]_{m\times n}$. It is generated by multiplying the columns of matrix $[R]_{m\times n}$ with the weights of criteria vector $[w_1, w_2, \dots, w_n]$, whose sum is equal to 1. The values of the weighted normalized decision matrix are calculated with the equation:

$$v_{ij} = w_i \times r_{ij} \quad (22)$$

where i = 1,2,…, m and j =1,2,…,n.

4. Determine the positive ideal and negative ideal solutions, termed as A^+ and A^-, respectively:

$$A^+ = \left\{\left(\max_i v_{ij} \mid j \in J^b\right), \left(\min_i v_{ij} \mid j \in J^c\right), i = 1, \dots, m\right\} = \{v_1^*, \dots, v_n^*\}_{ij} \tag{23}$$

$$A^- = \left\{\left(\min_i v_{ij} \mid j \in J^b\right), \left(\max_i v_{ij} \mid j \in J^c\right), i = 1, \dots, m\right\} = \{v_1^*, \dots, v_n^*\}_{ij} \tag{24}$$

where the index J^b is associated with the benefit criteria and the J^c is associated with cost criteria.

5. Calculate the distance measure, using the n-dimensional Euclidean distance. The separation S_{i^+} of each alternative from the ideal solution is determined according to the following expression:

$$S_{i^+} = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_{i^+}\right)^2}, \quad (i = 1,2,\dots, m) \tag{25}$$

Similarly, the separation S_{i^-} from the negative ideal solution is given as

$$S_{i^-} = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_{i^-}\right)^2}, \quad (i = 1,2,\dots, m) \tag{26}$$

6. Calculate the relative closeness coefficient, CC_i to the ideal solution. The relative closeness of the alternative a$_i$ with respect to A^+ is defined as

$$CC_i = \frac{S_{i^-}}{S_{i^+} + S_{i^-}}, \quad 0 < CC_i < 1, \ (i = 1,2,\dots, m) \tag{27}$$

7. Rank the preference order. For ranking alternatives using CC_i value, we can rank alternatives in decreasing order.

6.3. Survey on "prioritizing environmental, economic and social aspects in Life Cycle Sustainability Assessment"

An online survey was prepared with the aim of evaluating the relevance of a set of criteria according to the experts' judgments belonging to different sectors. The survey was mainly addressed to people belonging to the automotive sector, both as members of industry and as researchers in the field of automotive and sustainable transportation, and people working in the field of sustainability and Life Cycle Assessment in general. It was thought for experts in the field of sustainability and LCA. The survey was proposed to open public using media such as social networks, website, project communication channels; relevant actors on the automotive sector have been contacted for the promotion of the initiative, such as:

- Earpa (Earpa 2016);
- OEMs;
- Members of the Ministero dell'Ambiente e della Tutela del Territorio e del Mare (Miniambiente 2016);
- Roundtable for Product Social Impact Assessment (PRé Sustainability 2015);
- Rete Italiana LCA (Rete Italiana LCA 2016);
- Prè Consultant (Prè Consultant 2016);

6.3.1. Survey structure

The questionnaire is structured in four sections, each one having a different objective:

- Person description;
- Product representative of the given sector;
- Relevance of economic, environmental and social criteria;
- Comments and suggestions.

The “Person description” section is focused on the acquisition of general information about the user, such as working area, reference sector, research field, geographical work location, experience level.

The “Product representative of the given sector” section contains question about examples of a product/s representative for the reference sector, this would enable to better interpret the relevance values.

The “Relevance of economic, environmental and social criteria” section asks the user his/her opinion about relevance of a list of criteria. For this purpose a numerical scale was proposed: 1 = very unimportant; 2 = unimportant; 3 = medium; 4 = important; 5 = very important. Also the option “0= I don’t know” was proposed in order to honest and aware responses. The selected criteria are listed in Annex C. Concerning the economic part, the proposed criteria stemmed from the LCC context and represented the cost of the main life cycle stages of a product (raw material, production, use and EOL). For the environmental area, all the impact categories (mid-point) from the ILCD method were proposed, some of them were aggregated in order to enhance the user to fulfil the questionnaire so twelve criteria were proposed in total (Annex C). The social part compels sixteen criteria. They stemmed from the Roundtable for Product Social Metrics initiative, in particular the social topics proposed in the handbook (PRé Sustainability 2014).

All the questions were ‘mandatory’ fields in order to reach a full compilation of the questionnaire and so comparable results.

The ‘Comments and suggestions’ is mainly aimed at understanding the general opinion about the survey, the additional criteria, criticalities difficulties faced by the user.

6.3.2.**Results**

Quality of responses

The survey included a total of 147 responses, of which about 65% are almost completed. In the part aimed to understand the relevance of economic, environmental and social criteria the users could select a score between 1 and 5 or the score 0 which means "I don't know". Some of the completed responses showed a high number of "I don't know", for this reason those responses where this value was higher than the half of criteria (>16) have been excluded from the further evaluations. Finally, Table 32 shows that 90 responses have been furthermore evaluated.

Table 32 Number of responses from the online survey

Total of answers	147
Completed answers	96
Uncertain answers (number of 'don't know' > 16)	6
Sample used	90

Person description

The identification of user working area shows that users from academia have been the predominant ones, but that also Industry are represented by at least a 26% share; 14% from other field (consultant, government, etc.) (Figure 29).

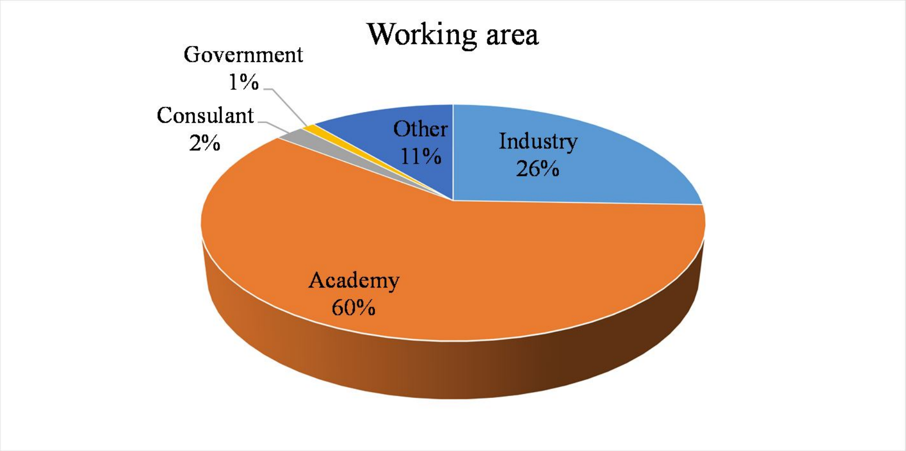

Figure 29 Working area distribution

Within the academy group the research field is mainly related to 'Life Cycle Assessment' (72%), whereas Social LCA and CSR correspond to 13% and 2% respectively (Figure 30). As shown in Figure 31 the most frequent reference sector of the industry group is the automotive one (43%) followed by the category 'other' in which the most frequent sector is the chemical products (Figure 31). The cause is probably related to the media used for the diffusion of the survey, some of them where particularly targeted to this sector which is indeed the focus of this research.

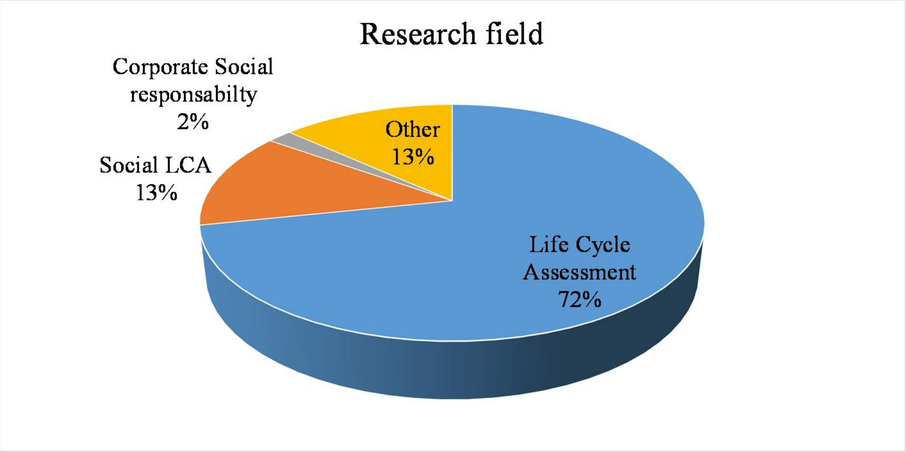

Figure 30 Academy research field distribution

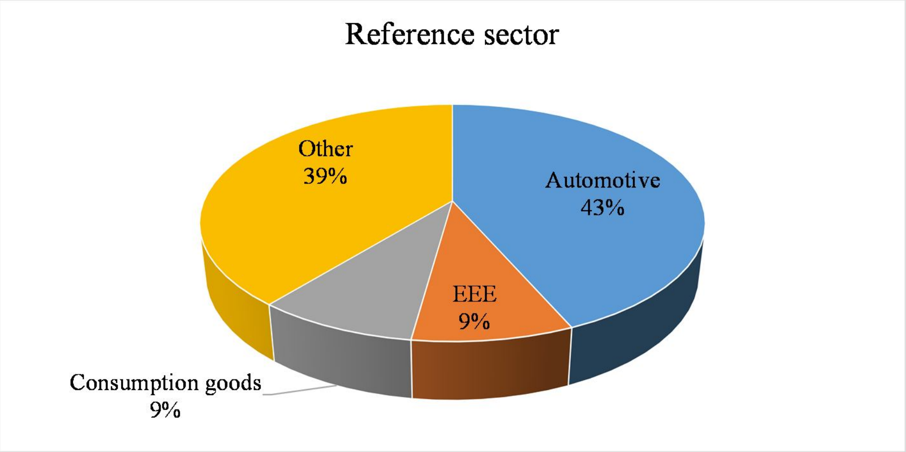

Figure 31 Reference sector distribution (‘other’ includes: Chemical products for building, industry, Sustainability consulting, Chemicals, Chemicals, Mechanical, all customer sectors, Environment, concrete, Glass industry)

The identification of user geographical work location on the basis of continents shows that European users have been the predominant ones (78%), followed by North America (11%) and South America (7%); in Europe 28% of answers are from Italy, but that also Germany, France, UK and Spain are represented by at least a 9% share (Figure 32).

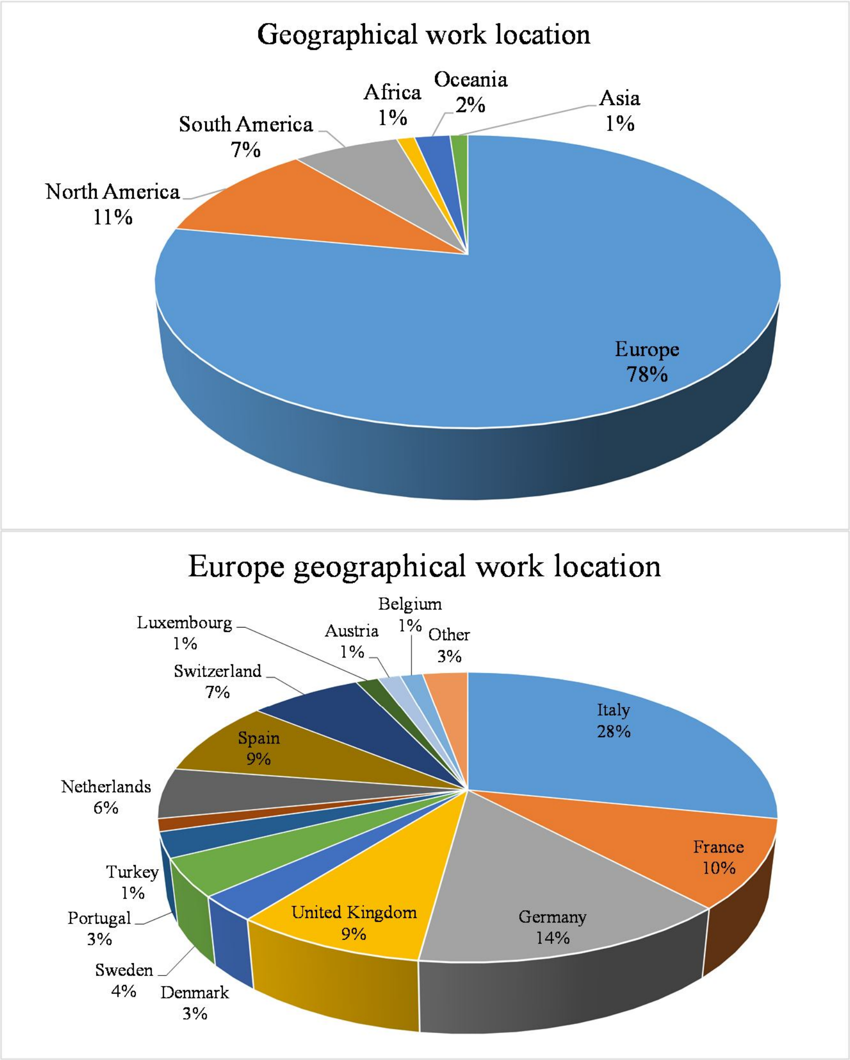

Figure 32 Geographical work location

Overall, people who took part to the survey have an experience level of less than 5 years in the 47%, whereas 32% have an experience between 5 and 10 years (Figure 33).

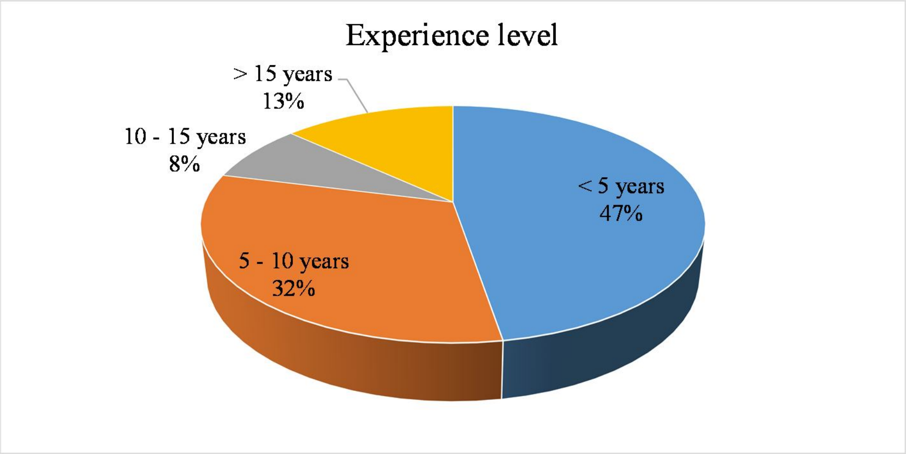

Figure 33 Experience level distribution

Product representative of the given sector

The wide variety of reported products have been analysed and classified according to main product categories (Table 33).

Table 33 List of product categories derived from the products reported in the survey as representative of the given sector

Product categories	**Products name**
Automotive and transport systems	Vehicles, vehicle components, transportation systems
Chemicals and materials	Glass, aluminium for packaging, other metals, polymers, composites
Construction products	Cement, concrete
Electrical and Electronic Equipment	Washing machine, mobile phone, fridges, software, screen
Food and agricultural products	Milk, pork meat, banana, pineapple, primary crop and livestock
Fuels, biofuels and energy systems	Photovoltaic, hydrogen, solar cells, electricity systems and technologies, bioenergy
Water	Water systems

Relevance of economic, environmental and social criteria

The relevance of the proposed criteria was analysed by means of graphs and indices from the descriptive statistics:

- Graphs: boxplot;
- Indices: median, mode, min and max.

These statistic information are presented first for the 'total population' (total number of responses) and then the relevance of all the criteria are analysed according to "working area" stratification. A particular focus is dedicated to the 'automotive group', which includes both people belonging to the industry (according to the reference sector) and those belonging to the academy (according to the selected product representative of your sector).

Figure 34, Figure 35 and Figure 36 show boxplot graph drawn for relevance score for economic, environmental and social criteria respectively. The boxplot provides min, max, median, first quartile (Q1) and third quartile (Q3) and represents the responses spread/distribution for each criteria.

Among the economic criteria the production cost has the larger median relevance, moreover its boxplot is comparatively short thus suggesting a high level of agreement concerning its relevance (Figure 34). The remaining criteria have a tall boxplot which means that a quite heterogeneous opinions exists about them. Raw material cost has a larger median relevance that the use and EOL stages costs.

As for the environmental indicators, some of them have the same median relevance but different distribution (i.e. $ADP_{el.}$ and ODP, or AP and PED). GWP has a relatively short boxplot, this suggests that overall users have a high level of agreement with each other, and it has the largest median relevance (5); whereas people hold quite different opinions about all the other indicators since spread data are observed (Figure 35). Overall, social criteria seem to have more compact observations (short boxplot) and only 6 out of 16 have spread responses. Overall, a median relevance between 3 and 4 is found and no criteria have a median of 5 (Figure 36).

Outliers have been examined but do not provide significant or additional element for the interpretation of the data spread. The statistic indices for all the criteria are minimum, maximum, median and mode (Table 34).

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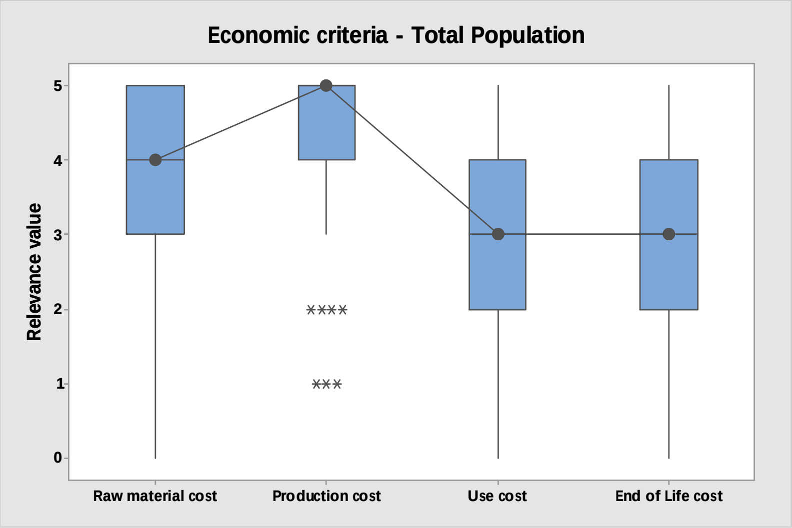


Figure 34 Boxplot relevance of economic criteria for the total population (*outliers)

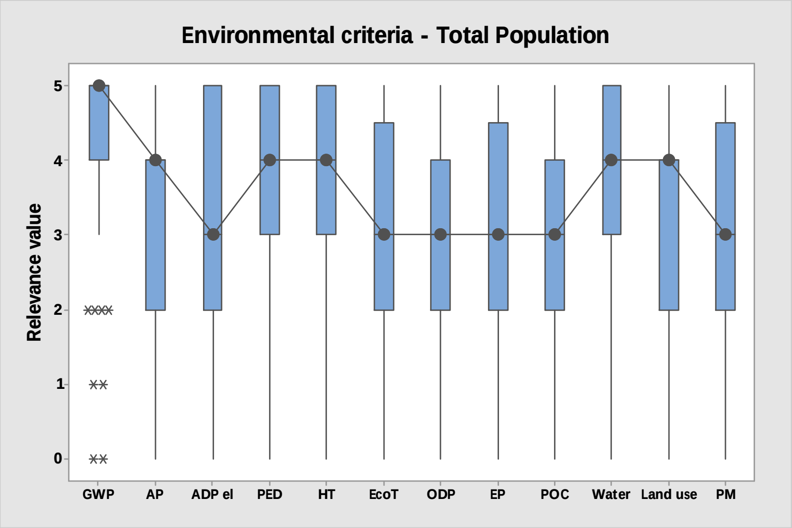


Figure 35 Boxplot relevance of environmental criteria for the total population (*outliers)

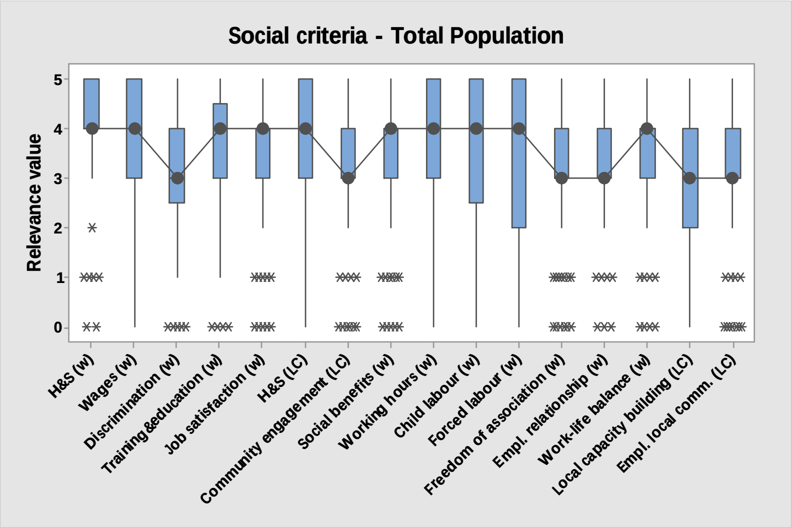


Figure 36 Boxplot relevance of social criteria for the total population (w= workers; LC=local communities) (*outliers)

Indeed, a unique and constant relevance for a given sustainability aspect can hardly be defined since this could depend on many aspects, time, geographic area and reference sector and working area among others, as demonstrated by the sector-specific literature (Del Duce et al. 2013) and the literature upon S-LCA (Dreyer et al. 2005; Jørgensen et al. 2012). For these reason the location of typically values according to specific feature of the people responding to the survey was observed.

Unfortunately the geographical work location of the users is not equally distributed among the several continents but the number of European people prevails (78%). This does not allow the analysis of the link between geographical location and relevance of criteria.

The analysis of the level of experience did not provide an evident relationship with relevance of criteria, contrary priority of criteria and working field showed a relevant correlation which has been examined by means of boxplot.

Stratification analysis of the economic criteria suggests that a more compact opinion exists for the raw material and production costs among the different working area, and the median values are overall higher that the ones of the use stage and EOL costs. In addition, for those two criteria more spread values are obtained. The automotive group provides the highest relevance values (in terms of median) among the working areas; raw materials and production are considered the most important, followed by the use stage and the EOL (Figure 37). Within the automotive group, people from the academy and those from the industry show a quite strong agreement (Figure 38). Moreover it can be observed that automotive group opinion is similar to the total population one for all the economic criteria with the exception of the use stage cost where the median relevance is higher. This results is in line with the expectations and confirm the relevance of the use stage in the vehicle sustainability.

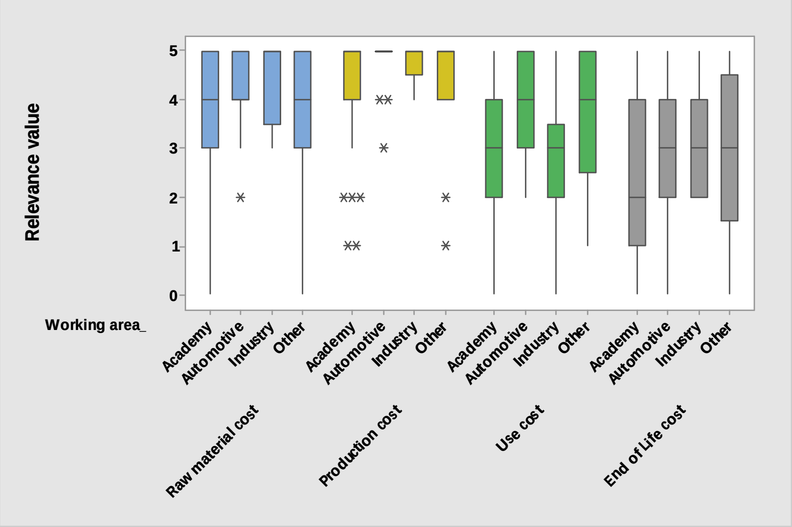


Figure 37 Boxplot relevance of economic criteria according to “working area” stratification (*outliers)

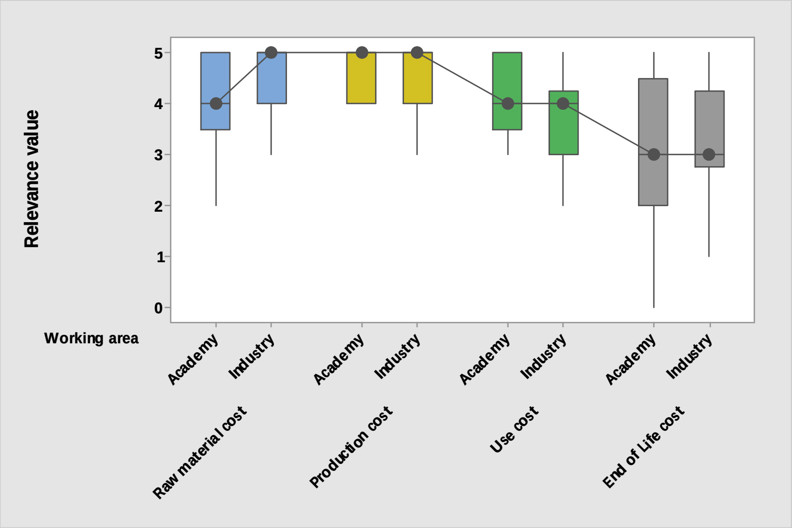


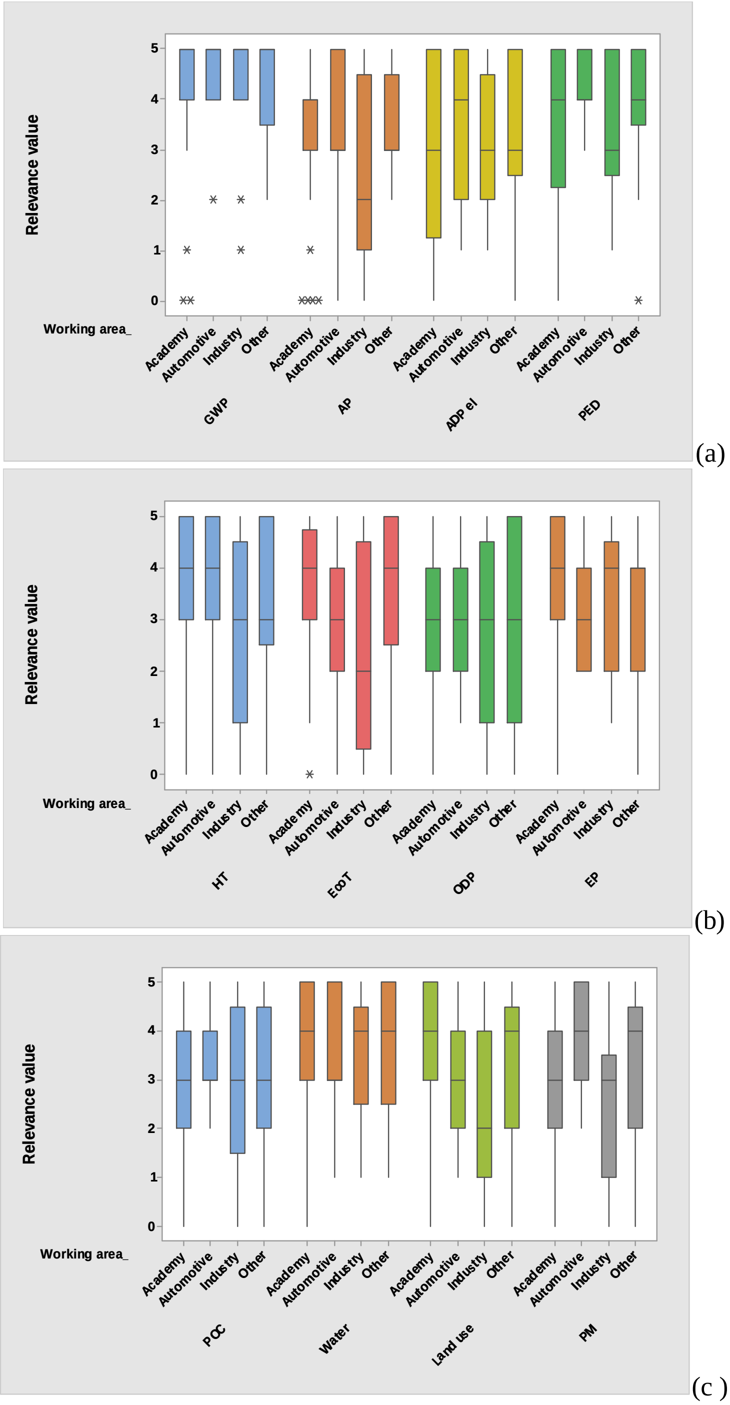
Figure 38 Boxplot relevance of economic criteria according to "working area" stratification within the automotive group (*outliers)

As for the environmental criteria, people from the automotive group hold a stronger agreement between each other than people from other working area, in fact boxplots are overall shorter (Figure 39).

The comparison between median values shows that ADP$_{el}$., PED, HT and PM have a larger median relevance for the automotive group than for academy and industry; GWP relevance is confirmed high (5) among different working areas (Figure 39 a). The relevance of EP, water consumption and land use is generally lower for the automotive group than for the academy opinion (Figure 39 b and c).

Overall, GWP is the most important environmental criteria for the automotive members, followed by resources consumption (ADP$_{el}$. and PED) and air quality (HT and PM) (Figure 40).

Within the automotive group, people from the academy and industry do not show a complete agreement, in fact the first give higher relevance values for 8 criteria out of 12 and only for the water consumption the industry provides a larger median than the academy (Figure 41).



(a)

(b)

(c)

Figure 39 Boxplot relevance of environmental criteria according to "working area" stratification (*outliers)

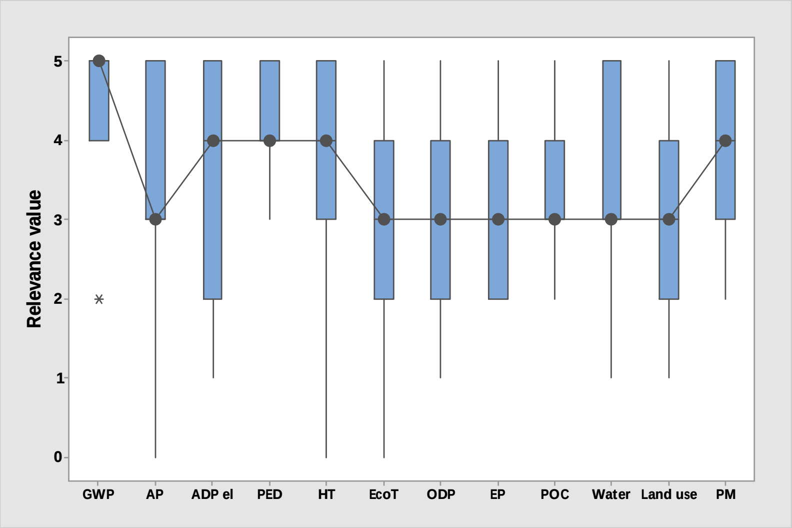


Figure 40 Boxplot environmental criteria from automotive group (*outliers)

The relationship between relevance of social criteria and working areas is less evident since slight difference can be observed among the median values (Figure 42). This outcome probably suggest a lower awareness or experience about the relevance of the proposed social criteria being all considered equally important by all the working areas.

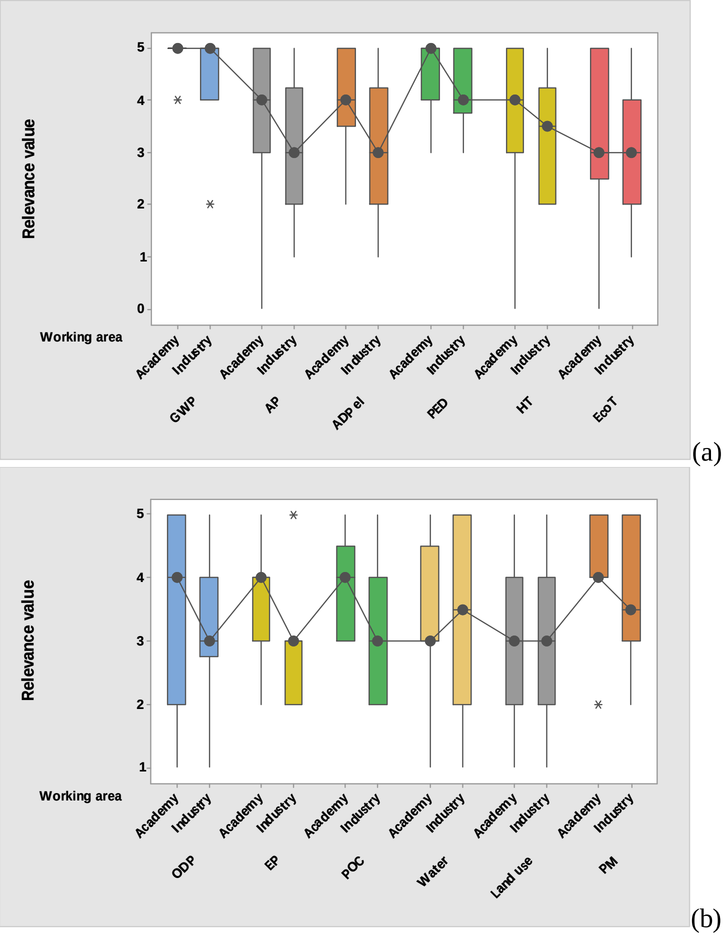
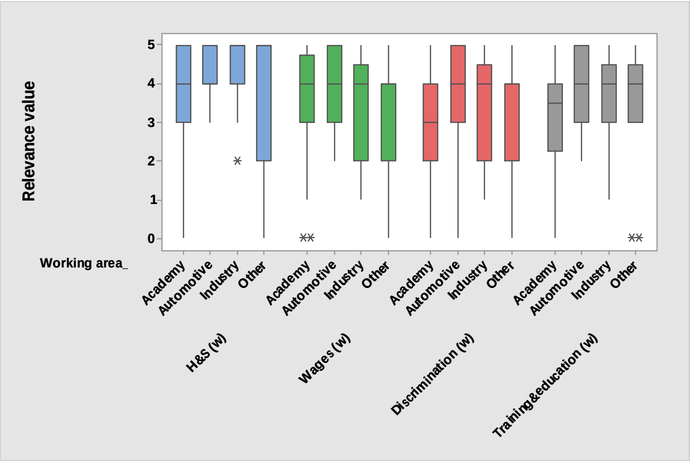
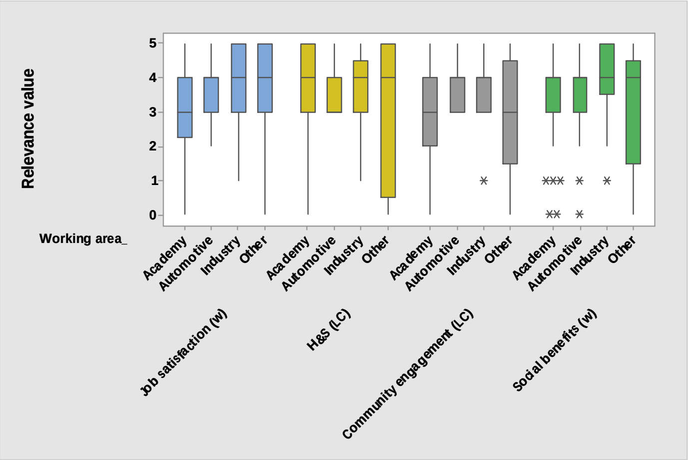


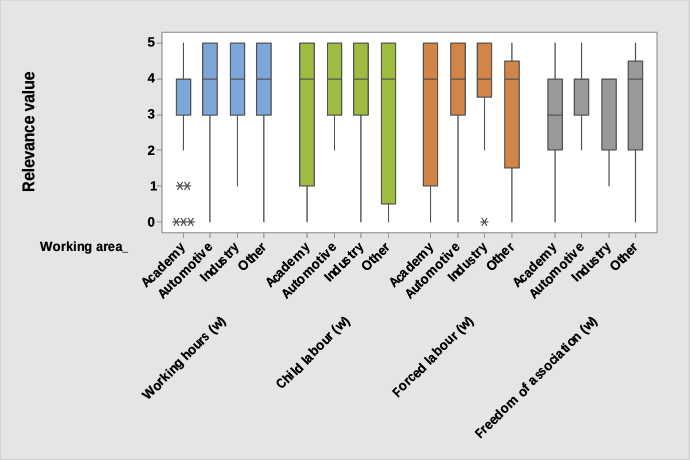
Figure 41 Boxplot relevance of environmental criteria according to “working area” stratification within the automotive group (*outliers)


Relevance value
0
1
2
3
4
5
Working area_
Academy
Automotive
Industry
Other
H&S (w)
Wages (w)
Discrimination (w)
Training&education (w)

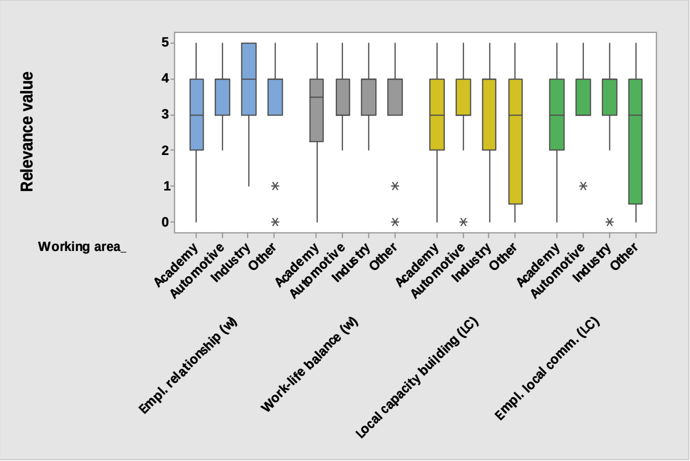
(a)


Relevance value
0
1
2
3
4
5
Working area_
Academy
Automotive
Industry
Other
Job satisfaction (w)
H&S (LC)
Community engagement (LC)
Social benefits (w)

(b)


Relevance value
0
1
2
3
4
5
Working area_
Academy
Automotive
Industry
Other
Working hours (w)
Child labour (w)
Forced labour (w)
Freedom of association (w)

(c)



(d)

Figure 42 Boxplot social criteria: comparison between working areas (*outliers)

The automotive group opinion holds a larger agreement than other groups and shows a higher median value in four criteria than the academy group (discrimination, community engagement, freedom of association and employment relationship). In this group a more homogeneous relevance is seen for the social criteria in fact 12 out of 16 reach a median value of 4 (no criteria have the relevance value 5) (Figure 43).

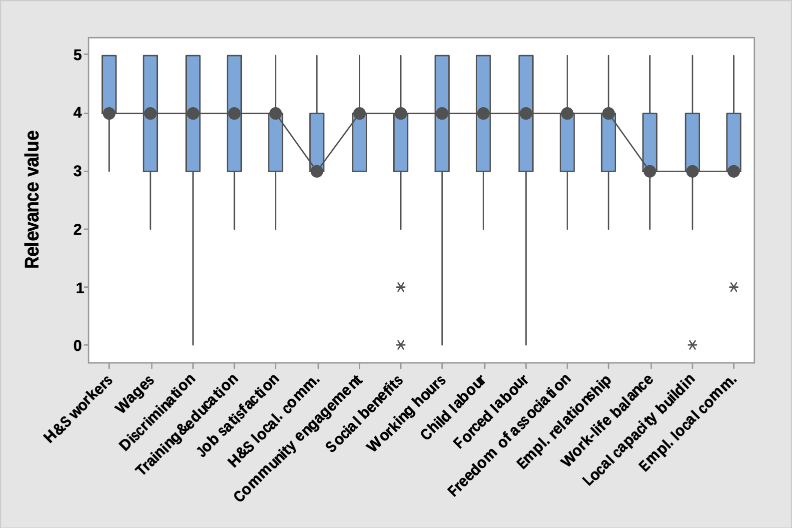
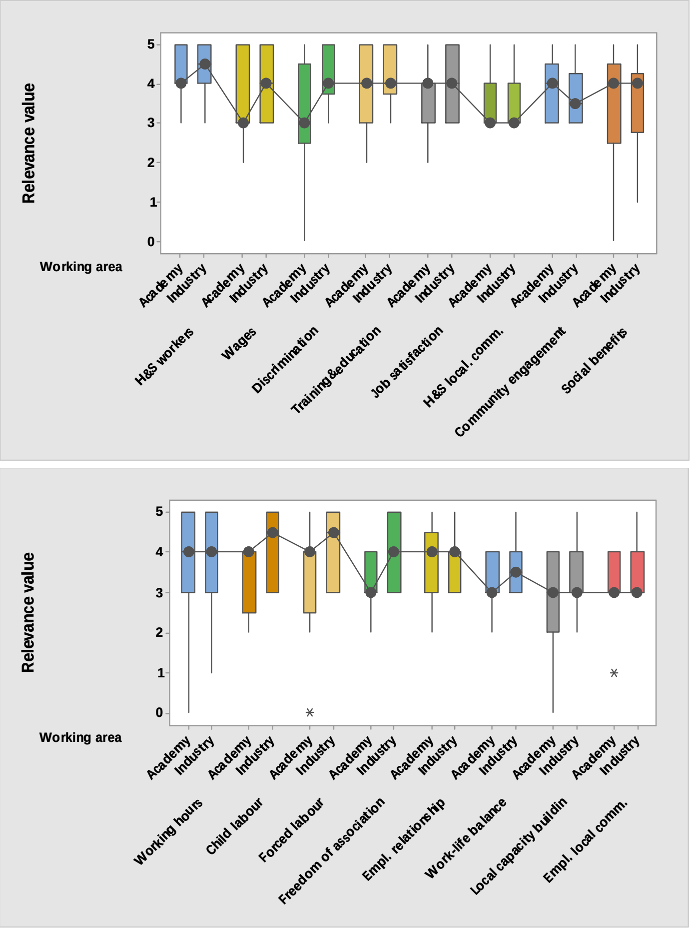


Figure 43 Boxplot social criteria from automotive group (*outliers)

Within the automotive group, people from the academy and industry do not show a complete agreement; overall the second give higher relevance values for 7 criteria out of 16 and only for the communities engagement the academy provides a larger median than the industry (Figure 44).



(a)

(b)

Figure 44 Boxplot relevance of social criteria according to "working area" stratification within the automotive group (*outliers)

The central tendency of a dataset is a single value that attempts to describe the central position within that set of data. Generally, the mean, median and mode are all valid measures of central tendency, but under different conditions, some measures of central tendency become more appropriate to use than others. The mean is one of the most popular but it is particularly susceptible to the influence of outliers; moreover, from a mathematical point of view, it is not a whole number and so for these reasons it is not appropriate for representing the central position of the relevance whose value, ranging between 1 and 5, corresponds to a specific scale of priority. The median is the middle score for a set of data that has been arranged in order of magnitude; it is less affected by outliers and skewed data for this reasons it is a good candidate for representing the central tendency of the relevance. However, it provides a whole number only when an odd number of scores is present. The mode is the most frequent score in the data set and it is normally used for categorical data where we wish to know which the most common category is. However, two problems affect the mode: it is not unique (it is not possible to select the best most when we have two or more values that share the highest frequency); it will not provide us with a very good measure of central tendency when the most common score is far away from the rest of the data in the data set.

Looking at the mode and median values of the automotive group (Table 34) it is possible to observe that for a certain number of criteria there are two or more modes, while median values are all whole numbers. This could suggest that median is the appropriate index to use as representative of the criteria weights.

Table 34 Min, Max, Median and Mode of the relevance of the criteria according to working areas (w=workers, LC=local communities)

Variable	Working area	Count	Min	Max	Median	Mode	No. for mode
Raw material cost	Academy	44	0	5	4	4	15
	Automotive	19	2	5	4	5	9
	Industry	13	3	5	5	5	8
	Other	13	0	5	4	5	5
	Total population	89	0	5	4	5	35
Production cost	Academy	44	1	5	5	5	28
	Automotive	19	3	5	5	5	16
	Industry	13	4	5	5	5	10
	Other	13	1	5	5	5	8
	Total population	89	1	5	5	5	62
Use cost	Academy	44	0	5	3	3	12
	Automotive	19	2	5	4	4	9
	Industry	13	0	5	3	2	5
	Other	13	1	5	4	5	4
	Total population	89	0	5	3	3	23
EOL cost	Academy	44	0	5	2	2	10
	Automotive	19	0	5	3	3	7
	Industry	13	2	5	3	2	5
	Other	13	0	5	3	3	4
	Total population	89	0	5	3	3	23
GWP	Academy	44	0	5	5	5	28
	Automotive	19	2	5	5	5	14
	Industry	13	1	5	5	5	9
	Other	13	2	5	5	5	9
	Total population	89	0	5	5	5	60

Variable	**Working area**	**Count**	**Min**	**Max**	**Median**	**Mode**	**No. for mode**
AP	Academy	44	0	5	4	4	18
	Automotive	19	0	5	3	3; 5	6
	Industry	13	0	5	2	1; 5	3
	Other	13	2	5	3	3	5
	Total population	89	0	5	4	4	26
$ADP_{el.}$	Academy	44	0	5	3	5	13
	Automotive	19	1	5	4	5	6
	Industry	13	1	5	3	2; 4; 5	3
	Other	13	0	5	3	3; 5	4
	Total population	89	0	5	3	5	26
PED	Academy	44	0	5	4	5	16
	Automotive	19	3	5	4	4; 5	8
	Industry	13	1	5	3	3; 5	4
	Other	13	0	5	4	4; 5	5
	Total population	89	0	5	4	5	33
HT	Academy	44	0	5	4	4	14
	Automotive	19	0	5	4	5	6
	Industry	13	0	5	3	3; 5	3
	Other	13	0	5	3	5	5
	Total population	89	0	5	4	5	26
EcoT	Academy	44	0	5	4	4	13
	Automotive	19	0	5	3	3	5
	Industry	13	0	5	2	0; 1; 5	3
	Other	13	0	5	4	5	4
	Total population	89	0	5	3	5	22
ODP	Academy	44	0	5	3	4	12
	Automotive	19	1	5	3	3	6
	Industry	13	0	5	3	1; 4; 5	3
	Other	13	0	5	3	3; 5	4
	Total population	89	0	5	3	3	21

Variable	**Working area**	**Count**	**Min**	**Max**	**Median**	**Mode**	**No. for mode**
EP	Academy	44	0	5	4	5	15
	Automotive	19	2	5	3	3	8
	Industry	13	1	5	4	4	4
	Other	13	0	5	4	4	5
	Total population	89	0	5	3	4; 5	22
POC	Academy	44	0	5	3	3	18
	Automotive	19	2	5	3	3	7
	Industry	13	0	5	3	2; 5	3
	Other	13	0	5	3	2	4
	Total population	89	0	5	3	3	29
Water	Academy	44	0	5	4	5	19
	Automotive	19	1	5	3	3	7
	Industry	13	1	5	4	4	5
	Other	13	1	5	4	5	4
	Total population	89	0	5	4	5	31
Land use	Academy	44	0	5	4	4; 5	15
	Automotive	19	1	5	3	2; 3; 4	5
	Industry	13	0	5	2	1; 4	3
	Other	13	0	5	4	4	4
	Total population	89	0	5	4	4	27
PM	Academy	44	0	5	3	3	13
	Automotive	19	2	5	4	5	7
	Industry	13	0	5	3	3	4
	Other	13	0	5	4	4	4
	Total population	89	0	5	3	3	23
Health and Safety (w)	Academy	44	0	5	4	4; 5	16
	Automotive	19	3	5	4	5	9
	Industry	13	2	5	5	5	7
	Other	13	0	5	5	5	7
	Total population	89	0	5	4	5	39

Variable	**Working area**	**Count**	**Min**	**Max**	**Median**	**Mode**	**No. for mode**
Wages (w)	Academy	44	0	5	4	4	16
	Automotive	19	2	5	4	3	8
	Industry	13	1	5	4	4	5
	Other	13	0	5	4	4	5
	Total population	89	0	5	4	4	29
Discrimination (w)	Academy	44	0	5	3	3	17
	Automotive	19	0	5	4	4; 5	6
	Industry	13	1	5	4	4	5
	Other	13	0	5	4	4	7
	Total population	89	0	5	3	4	28
Training and education (w)	Academy	44	0	5	3,5	4	13
	Automotive	19	2	5	4	4; 5	7
	Industry	13	1	5	4	4	6
	Other	13	0	5	4	4	6
	Total population	89	0	5	4	4	32
Job satisfaction (w)	Academy	44	0	5	3	3; 4	14
	Automotive	19	2	5	4	3; 4	7
	Industry	13	1	5	4	4	5
	Other	13	0	5	4	4	5
	Total population	89	0	5	4	4	31
Health and Safety (LC)	Academy	44	0	5	4	5	18
	Automotive	19	3	5	3	3	11
	Industry	13	1	5	4	4	5
	Other	13	0	5	4	5	4
	Total population	89	0	5	4	5	27
Community engagement (LC)	Academy	44	0	5	3	3	13
	Automotive	19	3	5	4	3	9
	Industry	13	1	5	4	4	7
	Other	13	0	5	3	3	4
	Total population	89	0	5	3	3	30

Variable	**Working area**	**Count**	**Min**	**Max**	**Median**	**Mode**	**No. for mode**
Social benefits (w)	Academy	44	0	5	4	4	21
	Automotive	19	0	5	4	4	9
	Industry	13	1	5	4	4; 5	5
	Other	13	0	5	4	4	4
	Total population	89	0	5	4	4	39
Working hours (w)	Academy	44	0	5	4	4	17
	Automotive	19	0	5	4	5	7
	Industry	13	1	5	4	5	5
	Other	13	0	5	4	4	5
	Total population	89	0	5	4	4	32
Child labour (w)	Academy	44	0	5	4	5	14
	Automotive	19	2	5	4	4	7
	Industry	13	0	5	4	4	5
	Other	13	0	5	4	5	6
	Total population	89	0	5	4	5	29
Forced labour (w)	Academy	44	0	5	4	5	17
	Automotive	19	0	5	4	4; 5	6
	Industry	13	0	5	4	4; 5	5
	Other	13	0	5	4	4	5
	Total population	89	0	5	4	5	31
Freedom of association (w)	Academy	44	0	5	3	4	14
	Automotive	19	2	5	4	3	8
	Industry	13	1	4	4	4	7
	Other	13	0	5	4	4	4
	Total population	89	0	5	3	4	32
Employment relationship (w)	Academy	44	0	5	3	3	17
	Automotive	19	2	5	4	4	9
	Industry	13	1	5	4	5	5
	Other	13	0	5	4	4	6
	Total population	89	0	5	3	4	30

Variable	**Working area**	**Count**	**Min**	**Max**	**Median**	**Mode**	**No. for mode**
Work-life balance (w)	Academy	44	0	5	3,5	4	15
	Automotive	19	2	5	3	3	10
	Industry	13	2	5	4	4	8
	Other	13	0	5	4	4	7
	Total population	89	0	5	4	4	37
Local capacity building (LC)	Academy	44	0	5	3	4	12
	Automotive	19	0	5	3	3	8
	Industry	13	0	5	4	4	5
	Other	13	0	5	3	3	4
	Total population	89	0	5	3	4	25
Employment (LC)	Academy	44	0	5	3	4	12
	Automotive	19	1	5	3	3	10
	Industry	13	0	5	4	4	7
	Other	13	0	5	3	4	4
	Total population	89	0	5	3	4	30

Comments and suggestions

The section is opened with a question which asks to the user to declare comments and suggestions about the whole survey or the specific criteria. All the suggestions and comments (22) can be grouped into three main classes: the first concerns comments about readability and difficulties in the survey filling; the second is about the awareness and expected results from the survey; the third includes comments about difficulties in the interpretation of criteria, especially the social one.

Overall, the responses analysis suggests that the priority level derived from the survey need to be kept separately according to the working area if high level of agreement, and so representativeness, would be guaranteed. Among the four working area groups, the automotive one provides a more compact response thus suggesting that a general agreement upon relevance of sustainability criteria could be observed. On the contrary, academia and industry provide still high heterogeneity. According to the person description, responses and the criteria prioritization speak for a specific geographic area (Europe), in fact few answers came from different areas. In conclusion, responses from the automotive group could be considered a good representation of the sector feeling, according to a European perspective, but if different sectors or geographical contexts would be analysed then such results would be necessary extended.

6.4. Calculation of sustainability criteria weights

The online survey was used to evaluate the relevance given by a pool of experts to the 32 sustainability criteria. Experts have evaluated each criterion using linguistic terms linked to the IFNs, in particular a 5 linguistic terms are used (1 = very unimportant; 2 = unimportant; 3 = medium; 4 = important; 5 = very important) (Table 35).

Table 35 Linguistic terms and corresponding fuzzy numbers (IFNs)

Linguistic terms	**Symbol**	**IFNs**	
Very Unimportant	VU	n_1	0.00
		n_2	0.00
		n_3	0.11
		n_4	0.22
Unimportant	U	n_1	0.11
		n_2	0.22
		n_3	0.33
		n_4	0.44
Medium	M	n_1	0.33
		n_2	0.44
		n_3	0.56
		n_4	0.67
Important	I	n_1	0.56
		n_2	0.67
		n_3	0.78
		n_4	0.89
Very Important	VI	n_1	0.78
		n_2	0.89
		n_3	1.00
		n_4	1.00

In this study it was assumed that the different groups, in terms of working area, taking part to the online survey could represent different decision makers groups, providing a different perspectives in the sustainability assessment of products. For this reason the judgment of these four experts groups was taken into account (Table 36).

Table 36 Decision makers' evaluation of sustainability criteria (linguistic terms)

	ID	**Criteria**	**D academy**	**D industry**	**D other**	**D automotive**
Economic	C1	Raw material cost	I	VI	I	I
	C2	Production cost	VI	VI	VI	VI
	C3	Use cost	M	M	I	I
	C4	EOL cost	U	M	M	M
Environmental	C5	GWP	VI	VI	VI	VI
	C6	AP	I	U	M	M
	C7	$ADP_{el.}$	M	M	M	I
	C8	PED	I	M	I	I

	ID	**Criteria**	**D academy**	**D industry**	**D other**	**D automotive**
Environmental	C9	HT	I	M	M	I
	C10	EcoT	I	U	I	M
	C11	ODP	M	M	M	M
	C12	EP	I	I	I	M
	C13	POCP	M	M	M	M
	C14	Water	I	I	I	M
	C15	Land use	I	U	I	M
	C16	PM	M	M	I	I
Social	C17	Health and Safety workers	I	VI	VI	I
	C18	Wages	I	I	I	I
	C19	Discrimination	M	I	I	I
	C20	Training and education	M	I	I	I
	C21	Job satisfaction	M	I	I	I
	C22	H&S local. comm.	I	I	I	M
	C23	Community engagement	M	I	M	I
	C24	Social benefits	I	I	I	I
	C25	Working hours	I	I	I	I
	C26	Child labour	I	I	I	I
	C27	Forced labour	I	I	I	I
	C28	Freedom of association	M	I	I	I
	C29	Employment relationship	M	I	I	I
	C30	Work-life balance	M	I	I	M
	C31	Local capacity building	M	I	M	M
	C32	Employment local community	M	I	M	M

Table 37 Decision makers' evaluation of sustainability criteria (fuzzy set)

ID	**Criteria**	**Fuzzy set**	**D academy**	**D industry**	**D other**	**D automotive**
C1	Raw material cost	n_1	0.56	0.78	0.56	0.56
		n_2	0.67	0.89	0.67	0.67
		n_3	0.78	1.00	0.78	0.78
		n_4	0.89	1.00	0.89	0.89
C2	Production cost	n_1	0.78	0.78	0.78	0.78
		n_2	0.89	0.89	0.89	0.89
		n_3	1.00	1.00	1.00	1.00
		n_4	1.00	1.00	1.00	1.00

ID	**Criteria**	**Fuzzy set**	**D** $_{\textbf{academy}}$	**D** $_{\textbf{industry}}$	**D** $_{\textbf{other}}$	**D** $_{\textbf{automotive}}$
C3	Use cost	n_1	0.33	0.33	0.56	0.56
		n_2	0.44	0.44	0.67	0.67
		n_3	0.56	0.56	0.78	0.78
		n_4	0.67	0.67	0.89	0.89
C4	EOL cost	n_1	0.11	0.33	0.33	0.33
		n_2	0.22	0.44	0.44	0.44
		n_3	0.33	0.56	0.56	0.56
		n_4	0.44	0.67	0.67	0.67
C5	GWP	n_1	0.78	0.78	0.78	0.78
		n_2	0.89	0.89	0.89	0.89
		n_3	1.00	1.00	1.00	1.00
		n_4	1.00	1.00	1.00	1.00
C6	AP	n_1	0.56	0.11	0.33	0.33
		n_2	0.67	0.22	0.44	0.44
		n_3	0.78	0.33	0.56	0.56
		n_4	0.89	0.44	0.67	0.67
C7	ADP$_{el.}$	n_1	0.33	0.33	0.33	0.56
		n_2	0.44	0.44	0.44	0.67
		n_3	0.56	0.56	0.56	0.78
		n_4	0.67	0.67	0.67	0.89
C8	PED	n_1	0.56	0.33	0.56	0.56
		n_2	0.67	0.44	0.67	0.67
		n_3	0.78	0.56	0.78	0.78
		n_4	0.89	0.67	0.89	0.89
C9	HT	n_1	0.56	0.33	0.33	0.56
		n_2	0.67	0.44	0.44	0.67
		n_3	0.78	0.56	0.56	0.78
		n_4	0.89	0.67	0.67	0.89
C10	EcoT	n_1	0.56	0.11	0.56	0.33
		n_2	0.67	0.22	0.67	0.44
		n_3	0.78	0.33	0.78	0.56
		n_4	0.89	0.44	0.89	0.67
C11	ODP	n_1	0.33	0.33	0.33	0.33
		n_2	0.44	0.44	0.44	0.44
		n_3	0.56	0.56	0.56	0.56
		n_4	0.67	0.67	0.67	0.67
C12	EP	n_1	0.56	0.56	0.56	0.33
		n_2	0.67	0.67	0.67	0.44
		n_3	0.78	0.78	0.78	0.56
		n_4	0.89	0.89	0.89	0.67
C13	POC	n_1	0.33	0.33	0.33	0.33
		n_2	0.44	0.44	0.44	0.44
		n_3	0.56	0.56	0.56	0.56
		n_4	0.67	0.67	0.67	0.67

ID	**Criteria**	**Fuzzy set**	**D** $_{\text{academy}}$	**D** $_{\text{industry}}$	**D** $_{\text{other}}$	**D** $_{\text{automotive}}$
C14	Water	n_1	0.56	0.56	0.56	0.33
		n_2	0.67	0.67	0.67	0.44
		n_3	0.78	0.78	0.78	0.56
		n_4	0.89	0.89	0.89	0.67
C15	Land use	n_1	0.56	0.11	0.56	0.33
		n_2	0.67	0.22	0.67	0.44
		n_3	0.78	0.33	0.78	0.56
		n_4	0.89	0.44	0.89	0.67
C16	PM	n_1	0.33	0.33	0.56	0.56
		n_2	0.44	0.44	0.67	0.67
		n_3	0.56	0.56	0.78	0.78
		n_4	0.67	0.67	0.89	0.89
C17	Health and Safety workers	n_1	0.56	0.78	0.78	0.56
		n_2	0.67	0.89	0.89	0.67
		n_3	0.78	1.00	1.00	0.78
		n_4	0.89	1.00	1.00	0.89
C18	Wages	n_1	0.56	0.56	0.56	0.56
		n_2	0.67	0.67	0.67	0.67
		n_3	0.78	0.78	0.78	0.78
		n_4	0.89	0.89	0.89	0.89
C19	Discrimination	n_1	0.33	0.56	0.56	0.56
		n_2	0.44	0.67	0.67	0.67
		n_3	0.56	0.78	0.78	0.78
		n_4	0.67	0.89	0.89	0.89
C20	Training and education	n_1	0.33	0.56	0.56	0.56
		n_2	0.44	0.67	0.67	0.67
		n_3	0.56	0.78	0.78	0.78
		n_4	0.67	0.89	0.89	0.89
C21	Job satisfaction	n_1	0.33	0.56	0.56	0.56
		n_2	0.44	0.67	0.67	0.67
		n_3	0.56	0.78	0.78	0.78
		n_4	0.67	0.89	0.89	0.89
C22	Health and Safety local community	n_1	0.56	0.56	0.56	0.33
		n_2	0.67	0.67	0.67	0.44
		n_3	0.78	0.78	0.78	0.56
		n_4	0.89	0.89	0.89	0.67
C23	Community engagement	n_1	0.33	0.56	0.33	0.56
		n_2	0.44	0.67	0.44	0.67
		n_3	0.56	0.78	0.56	0.78
		n_4	0.67	0.89	0.67	0.89

ID	**Criteria**	**Fuzzy set**	$D_{academy}$	$D_{industry}$	D_{other}	$D_{automotive}$
C24	Social benefits	n_1	0.56	0.56	0.56	0.56
		n_2	0.67	0.67	0.67	0.67
		n_3	0.78	0.78	0.78	0.78
		n_4	0.89	0.89	0.89	0.89
C25	Working hours	n_1	0.56	0.56	0.56	0.56
		n_2	0.67	0.67	0.67	0.67
		n_3	0.78	0.78	0.78	0.78
		n_4	0.89	0.89	0.89	0.89
C26	Child labour	n_1	0.56	0.56	0.56	0.56
		n_2	0.67	0.67	0.67	0.67
		n_3	0.78	0.78	0.78	0.78
		n_4	0.89	0.89	0.89	0.89
C27	Forced labour	n_1	0.56	0.56	0.56	0.56
		n_2	0.67	0.67	0.67	0.67
		n_3	0.78	0.78	0.78	0.78
		n_4	0.89	0.89	0.89	0.89
C28	Freedom of association	n_1	0.33	0.56	0.56	0.56
		n_2	0.44	0.67	0.67	0.67
		n_3	0.56	0.78	0.78	0.78
		n_4	0.67	0.89	0.89	0.89
C29	Employment Relationship	n_1	0.33	0.56	0.56	0.56
		n_2	0.44	0.67	0.67	0.67
		n_3	0.56	0.78	0.78	0.78
		n_4	0.67	0.89	0.89	0.89
C30	work-life balance	n_1	0.33	0.56	0.56	0.33
		n_2	0.44	0.67	0.67	0.44
		n_3	0.56	0.78	0.78	0.56
		n_4	0.67	0.89	0.89	0.67
C31	Local capacity building	n_1	0.33	0.56	0.33	0.33
		n_2	0.44	0.67	0.44	0.44
		n_3	0.56	0.78	0.56	0.56
		n_4	0.67	0.89	0.67	0.67
C32	Employment local community	n_1	0.33	0.56	0.33	0.33
		n_2	0.44	0.67	0.44	0.44
		n_3	0.56	0.78	0.56	0.56
		n_4	0.67	0.89	0.67	0.67

The aggregated IF decision matrix is then calculated by means of the formula 13-16 and the values are reported in Table 38.

Table 38 Aggregated IF decision matrix

ID	**Criteria**	**Aggregated IF decision matrix**			
		n1	n2	n3	n4
C1	Raw material cost	0.56	0.72	0.83	1.00
C2	Production cost	0.78	0.89	1.00	1.00
C3	Use cost	0.33	0.56	0.67	0.89
C4	EOL cost	0.11	0.39	0.50	0.67
C5	GWP	0.78	0.89	1.00	1.00
C6	AP	0.11	0.44	0.56	0.89
C7	$ADP_{el.}$	0.33	0.50	0.61	0.89
C8	PED	0.33	0.61	0.72	0.89
C9	HT	0.33	0.56	0.67	0.89
C10	EcoT	0.11	0.50	0.61	0.89
C11	ODP	0.33	0.44	0.56	0.67
C12	EP	0.33	0.61	0.72	0.89
C13	POCP	0.33	0.44	0.56	0.67
C14	Water	0.33	0.61	0.72	0.89
C15	Land use	0.11	0.50	0.61	0.89
C16	PM	0.33	0.56	0.67	0.89
C17	Health and Safety workers	0.56	0.78	0.89	1.00
C18	Wages	0.56	0.67	0.78	0.89
C19	Discrimination	0.33	0.61	0.72	0.89
C20	Training and education	0.33	0.61	0.72	0.89
C21	Job satisfaction	0.33	0.61	0.72	0.89
C22	Health and Safety local community	0.33	0.61	0.72	0.89
C23	Community engagement	0.33	0.56	0.67	0.89
C24	Social benefits	0.56	0.67	0.78	0.89
C25	Working hours	0.56	0.67	0.78	0.89
C26	Child labour	0.56	0.67	0.78	0.89
C27	Forced labour	0.56	0.67	0.78	0.89
C28	Freedom of association	0.33	0.61	0.72	0.89
C29	Employment relationship	0.33	0.61	0.72	0.89
C30	Work-life balance	0.33	0.56	0.67	0.89
C31	Local capacity building	0.33	0.50	0.61	0.89
C32	Employment local community	0.33	0.50	0.61	0.89

The distance from the intuitionistic fuzzy negative ideal solution (IFNIS), termed D_j^-, and from the intuitionistic fuzzy positive ideal solution (IFPIS), termed D_j^+ are calculated (Table 39). After the closeness coefficient and weight of each criteria are calculated (Table 39).

Table 39 Sustainability criteria weights

ID	**Criteria**	D_j^-	D_j^+	$\acute{C}_j$	w_j
C1	Raw material cost	1.399	0.324	0.812	0.038
C2	Production cost	1.670	0.000	1.000	0.047
C3	Use cost	1.083	0.657	0.622	0.029
C4	EOL cost	0.716	1.027	0.411	0.019
C5	GWP	1.670	0.000	1.000	0.047
C6	AP	0.923	0.923	0.500	0.024
C7	$\mathrm{ADP}_{\mathrm{el.}}$	1.027	0.716	0.589	0.028
C8	PED	1.141	0.603	0.654	0.031
C9	HT	1.083	0.657	0.622	0.029
C10	EcoT	0.978	0.871	0.529	0.025
C11	ODP	0.839	0.839	0.500	0.024
C12	EP	1.141	0.603	0.654	0.031
C13	POC	0.839	0.839	0.500	0.024
C14	Water	1.141	0.603	0.654	0.031
C15	Land use	0.978	0.871	0.529	0.025
C16	PM	1.083	0.657	0.622	0.029
C17	Health and Safety workers	1.457	0.272	0.843	0.040
C18	Wages	1.281	0.401	0.762	0.036
C19	Discrimination	1.141	0.603	0.654	0.031
C20	Training and education	1.141	0.603	0.654	0.031
C21	Job satisfaction	1.141	0.603	0.654	0.031
C22	Health and Safety local community	1.141	0.603	0.654	0.031
C23	Community engagement	1.083	0.657	0.622	0.029
C24	Social benefits	1.281	0.401	0.762	0.036
C25	Working hours	1.281	0.401	0.762	0.036
C26	Child labour	1.281	0.401	0.762	0.036
C27	Forced labour	1.281	0.401	0.762	0.036
C28	Freedom of association	1.141	0.603	0.654	0.031
C29	Employment relationship	1.141	0.603	0.654	0.031
C30	Work-life balance	1.083	0.657	0.622	0.029
C31	Local capacity building	1.027	0.716	0.589	0.028
C32	Employment local community	1.027	0.716	0.589	0.028

7. Life Cycle Sustainability Assessment application to lightweight solutions

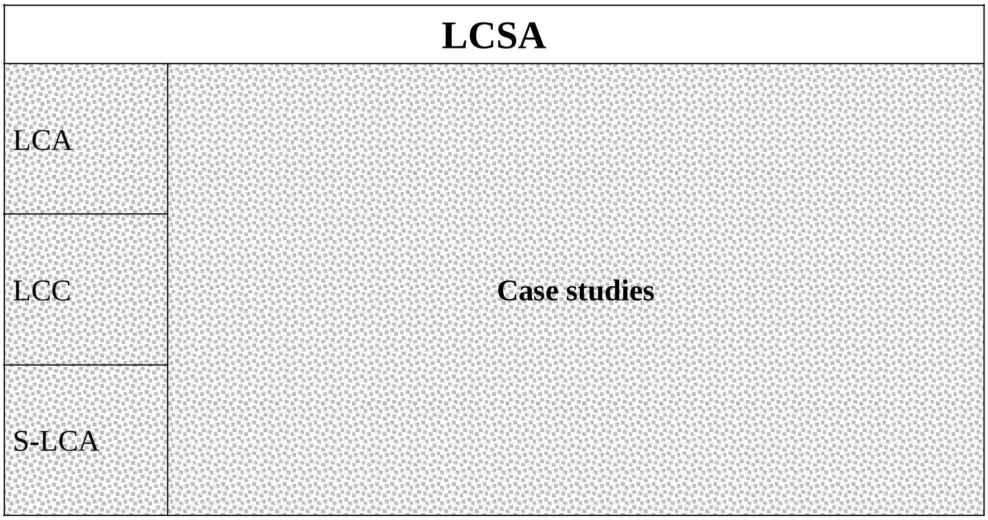


Figure 45 Scheme of research contributions to LCSA methodology: LCSA case studies

All the arguments presented throughout the previous chapters are here integrated and applied to two case studies regarding the LCSA of vehicle components (Figure 45). The first study regards a part of the suspension system (knuckle) (cfr. §7.1), whereas the second one deals with the comparison of two design solutions for a dashboard panel (cfr. §7.2).

Overall, the LCSA approach is depicted in Figure 46. First, the goal and scope is defined, considering the inherent differences of LCA, LCC and S-LCA. As for the S-LCA, the conceptual map presented in Chapter 5 represents the guide for facing goal and scope steps. Then data collection is carried out by means of specific templates where data useful for the economic, environmental and social assessment are integrated in a unique questionnaire specifically developed and shared with companies involved in the project; however the inventory analysis is carried out for each technique separately. The following phase, named impact assessment, regards the data inventory elaboration; it is developed separately for each methodology since they involve different data analysis. In the LCA, data from inventory are elaborated in the sense of impact assessment; in the LCC aggregation and interpretation of costs is developed; in the S-LCA the Type I method provides aggregation and evaluation of performances. Outcomes are then integrated and interpreted with the aim of evaluating compensations, stakeholder points of view and other important parameters affecting the final results.

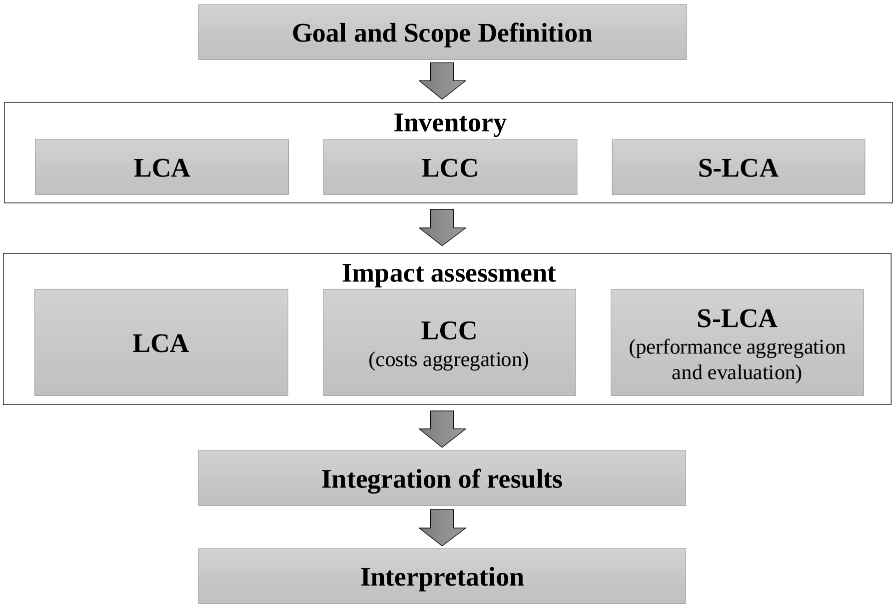


Figure 46 LCSA approach for the two case studies

The two case studies gave the opportunity to deepen different aspects of the LCSA. One of the main value of case study 1 (knuckle) is the involvement of the companies responsible for semi-manufactured product and component production, both in the data gathering and discussion. This enables to treat the following key aspects:

- LCSA settings, in particular goal and scope and inventory phases;
- S-LCA data collection at site level;
- Application of the quantitative approach proposed in the Handbook for Product Social Impact Assessment;
- Discussion about the following aspects:
  - Experience in the CSR elements (i.e. stakeholder engagement, materiality);
  - Use and contribution of the LCSA results;
  - Social indicators applicability and exhaustiveness, and relevant stakeholder groups.

Case study 2 (dashboard) concerns comparison between two design solutions; moreover the following key aspects are questioned:

- LCSA settings, in particular goal and scope and inventory phases;
- S-LCA data collection at site level;
- LCA and LCC data collection concerning an innovative material for component lightweighting (Hollow Glass Microspheres);

- Application of the TOPSIS method to integrate LCA, LCC and S-LCA results.

7.1. Case study 1: suspension system

This case study was developed within a mirror project in collaboration with Magneti Marelli and the car manufacturer. It was Magneti Marelli commitment to let the main suppliers to give their contribution for the consistency of the study, by involving them to provide the necessary data.

7.1.1.Product description

The knuckle is a part of the suspension system and takes part to the steering system; its principal roles are to support the vertical weight of the vehicle and attach the wheel and braking components to the suspensions (Figure 47). The suspension system comprises several individual components (i.e. control arms, cross-members, axles, knuckles, brake discs and drums) and is responsible for the following basic functions: maintain correct vehicle ride height, reduce the effect of shock forces, maintain correct wheel alignment, support vehicle weight, keep the tires in contact with the road, and control the vehicle's direction of travel.

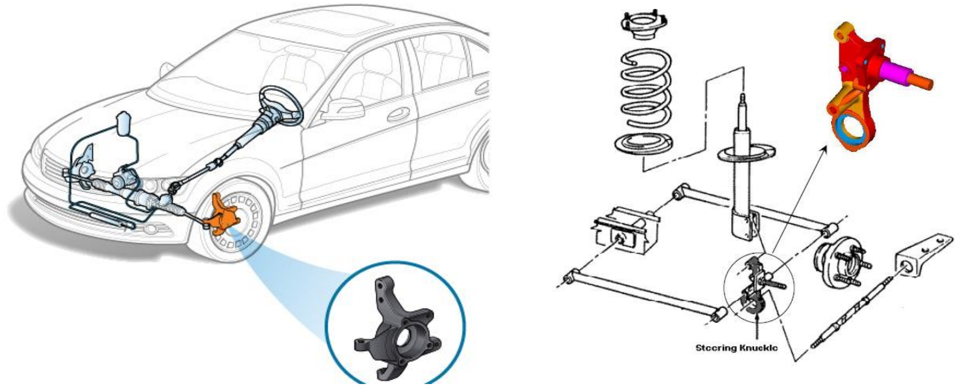


Figure 47 Location of knuckle wheel carrier in vehicle suspension system

The knuckle attaches to the suspension points, such as upper and lower control arms (via ball joints or pinch bolts), struts, and/or tie rod ball joints. The bearing and caliper are typically bolted to the knuckle (Figure 48).

Knuckles are typically custom designed for each application per customer vehicle and loading requirements. Knuckles are generally machined from ductile iron or aluminium depending on customer preference for cost versus mass savings. Depending on the vehicle model, its weight ranges between 5 and 6 kilogram per piece with a total weight of 20-24 kilograms for the whole vehicle. The suspension system is generally responsible for the 10-15% of the total weight of a vehicle, therefore light weighting analysis generally takes such modules into account.

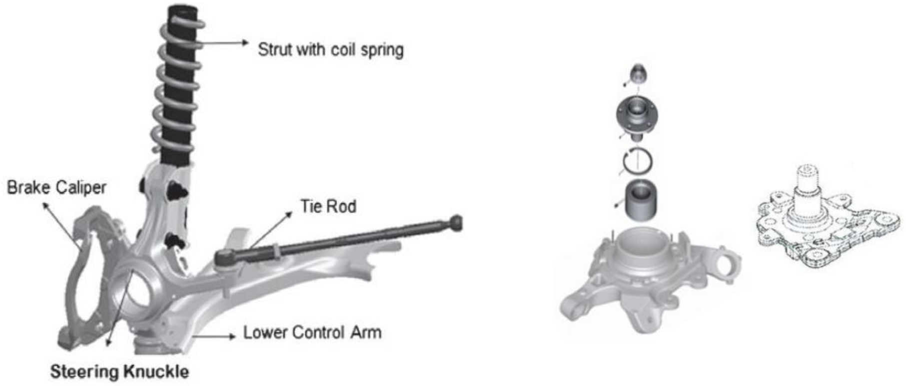


Figure 48 Assembly scheme of knuckle on suspension system (left) steering knuckle exploded view (right)

The steering knuckle of front suspension is produced through a sand casting process from cast iron scraps firstly melted in an electric furnace, then after process of refining is sent to another plant to be painted through cataphoresis process. The last process of machining, deburring, washing and DMC marking is managed by Magneti Marelli plant before send the item to the car manufacturer plant for the assembly of the remaining sub-components: nut, hub, segger, bearing , knuckle and for the final assembly on suspension system.

Table 40 reports the principal features of the knuckle, especially focusing on the production technology and the relative suppliers involved.

Table 40 Technical data of knuckle wheel carrier design solution (*the references of car manufacturer, semi-manufactured product and technology suppliers cannot be disclosed due to confidentiality reasons)

Weight (kg)	5.14	
Material	Cast iron	
Manufacturing		
Production technology	**Supplier**	**Location**
Die Casting	Company A*	Poland (EU)
Painting	Company B*	Poland (EU)
Refining	Magneti Marelli	Poland (EU)
Assembly of sub-components	Car manufacturer*	Germany (EU)
Assembly of component on vehicle	Car manufacturer*	Germany (EU)

7.1.2. Goal and Scope Definition

The two main companies involved in this analysis – Magneti Marelli and the car manufacturer – are already active in the Life Cycle Assessment application to their products. At the same time they develop or take part in Corporate Social Responsibility reporting at organization level.

Since this was the first project concerning LCSA, the following questions have been presented to the members of two companies in order to define which the expectations are concerning to the LCSA application. The first group of questions was addressed to people covering positions related to the general company management (i.e. general director, marketing) and were about how LCSA are intended to be used:

- What would be the value added of LCSA results, compared to the analyses and activities already carried out?
- How would LCSA results be used? Internally or externally?
- Could LCSA support the company at strategic level?

The second group of questions, addressed to people covering positions related to sustainability (i.e. R&D, Environment Health & Safety), is related to some of the most important principles of the CSR context:

- How the materiality analysis is addressed within the Company?
- Which are the relevant stakeholder groups for the Company?
- Are there already stakeholder involvement initiatives?
- Which are the most important concerns asked by stakeholders about the product?
- How the stakeholder groups can be involved during the LCSA development?

Overall, both companies claimed the importance of LCSA as a supporting tool to “identify the main sustainability hotspots in the product life cycle and therefore guide strategy development” and provide elements for production decisions. The value added of the LCSA is seen in its capability to “increase the significance of our studies and the awareness of the company’s impacts within society” and “help decision makers finding the right trade-off among the three pillars of sustainability towards a more sustainable product and production. We can not only check the three pillars of sustainability in the same time but the integration and finding the best compromise among them”. This project represents the first experience for both Companies, in addition, due to the young level of maturity of the methodology, they expect to use the LCSA outcomes internally in order to improve awareness upon these aspects and to test the potentiality of this methodology.

Context representation

According to the approach proposed by (Hu et al. 2013; Stefanova et al. 2014) the goal and scope of LCSA should include an analysis and a description of the socio-economic-environmental context characterizing the product value chain.

The overall goal of this LCSA study is to assess the sustainability of the entire knuckle life cycle, by taking into account its current value chain which involves different actors in different Countries.

The component is produced by Magneti Marelli ® (MM hereafter), which is the primary supplier of the car manufacturer for this specific component which is mounted over different vehicle models. MM has one single plant, located in Poland, dedicated to this given product. The main body of the knuckle (semi-manufactured) is provided by Company A whose plant is located in Poland too. In the same industrial district, it is also located the plant of Company B which is responsible for the painting process. The assembly of the component to the vehicle is done in different plants of the car manufacturer, located in Germany, responsible for different models.

Therefore, two Countries are involved in the production stage: Germany and Poland. Poland is the second largest producer of passenger cars, after the Czech Republic, in Europe (Bulinski 2010). For instance, the Opel Astra III and IV, the Fiat Panda and the Fiat 500, the Lancia Ypsilon, the Ford Ka, and the Chevrolet Aveo are produced in Poland. However, another important subsector is the production of car engines and other parts, used mainly in the production process of vehicles in other factories (i.e. engines for Toyota, Peugeot and Citroen). At present 136 000 people are employed in this sector, corresponding to 5% of all those employed in the industry (Bulinski 2010). The average monthly remuneration in the sector amounted to PLN 3,325 in 2009 and was slightly higher than the average for industry, which is PLN 3,315, and the national average (PLN 3,288) (Bulinski 2010).

Germany is Europe's number one automotive market in production and sales terms; it is conveniently located next to Poland, the biggest Eastern European market with passenger car unit sales of 325,000 in 2014. The automotive industry is the largest industry sector in Germany with a workforce of around 775,000 in 2014. No other country in Europe has a comparable concentration of auto-related R&D, design, supply, manufacturing, and assembly facilities (Di Bitonto and Germany Trade and Invest 2015).

In Germany, 92% of employment in the automotive is in large enterprises, while in Poland only 65% are large companies and 40% are medium (Figure 49).

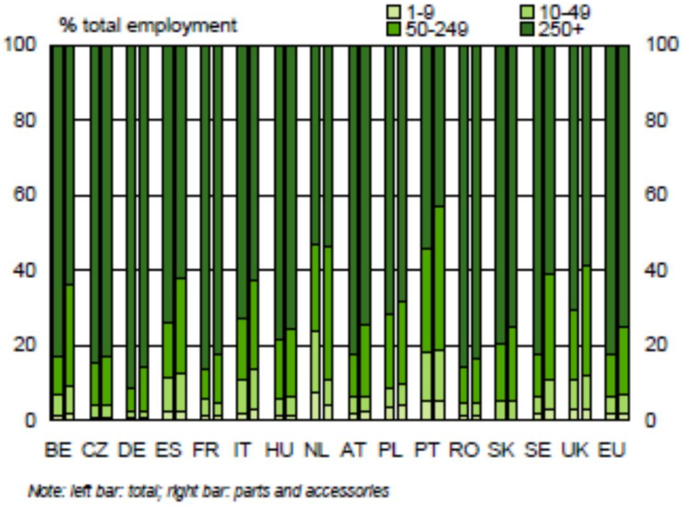


Figure 49 Employment by size of companies in the automotive sector (Ward and Loire 2008)

Looking at the divisions of employment, in Poland more than 40% are employed in parts and accessories and in Germany 60% are employed in motor vehicle (Figure 50).

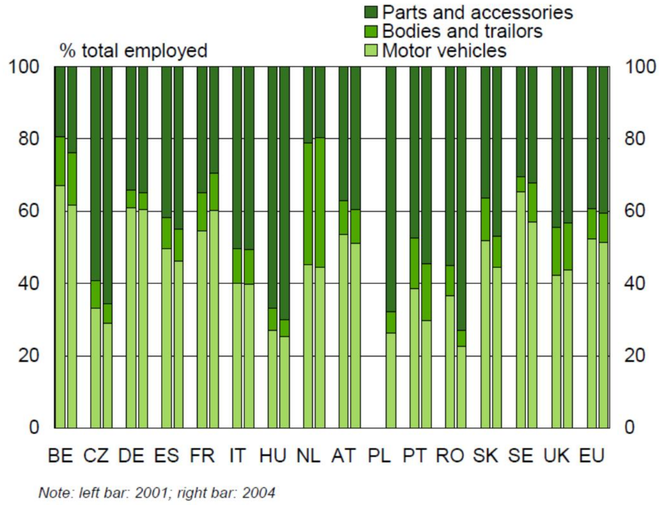


Figure 50 Division of employment in the automotive sector by sub-sector (Ward and Loire 2008)

For this sector[11] the Net Monthly Income in Germany is 2,569 Euros (PPP $ 2,176), considering both male and female employees, and 37.6 of weekly hours, corresponding to the hours paid for[12]. The Net Monthly Income in Poland is 2,593 PLN (PPP $ 931)[13], and 42.9 of weekly hours, corresponding to the hours actually worked[14].

Perspective

The perspective is generally defined only for the LCC, while for the LCA and S-LCA it is less clearly specified. According to the review outcomes presented in the previous chapter, different perspectives can be considered, a list of them is provided in Table 41 for each technique.

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[11] for the manufacturing sector as defined by the International Standard Industrial Classification of Economic Activities in ISIC Rev. 3-D and ISIC Rev. 2-3 (http://laborsta.ilo.org/)

[12] http://www.worldsalaries.org

[13] http://www.worldsalaries.org/; for the transport-communication sector as defined in ISIC Rev. 3-D and ISIC Rev. 2-3 by the International Standard Industrial Classification of Economic Activities. Transport-Communication (http://laborsta.ilo.org/)

[14] http://www.worldsalaries.org/

Table 41 Perspective types in the Life Cycle techniques *(Hunkeler et al. 2008; Swarr et al. 2011); ** (Zanchi et al. 2016)

	Perspective types		
LCA	Multi-stakeholder/who develops the analysis		
LCC*	Producer	Consumer	Society
S-LCA**	Company	Region	State

For this application, more efforts are done in order to better define the point of view of the study even for LCA and S-LCA and in the whole sustainability assessment.

Depending on the analysis perspective the results from this study could give different levels of information.

The first level is a general improvement in the knowledge about environmental, economic and social sustainability related to value chain of this product useful for both user and producer. If the producer perspective – MM or the car manufacturer - is applied, then the outcomes could give insight about the sustainability of the supply chain, while in the case of user perspective even further stages (use, EOL) could be included in the assessment, according to the system boundaries (Figure 51). The results could guide choices in the product improvement, to meet stakeholder satisfaction and requests.

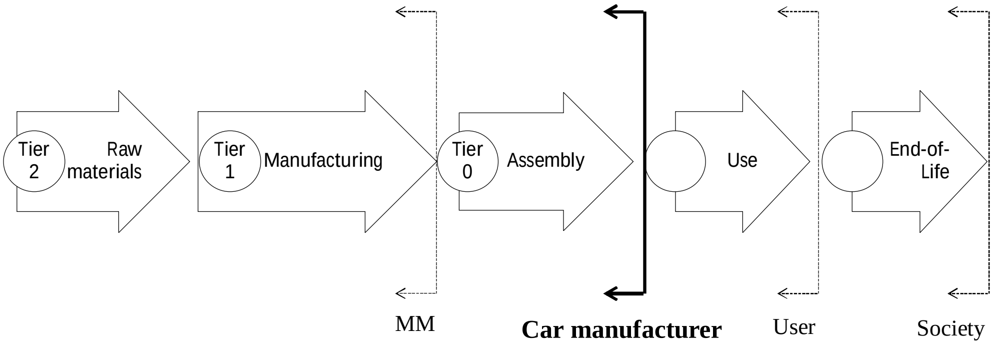


Figure 51 Life cycle stages and perspectives

For the case study at hand, the producer (MM or the car manufacturer) or company perspective is applied, in particular the perspective of the car manufacturer which is involved in the assembly stage of the final product. The consumer perspective is considered less interesting since the consumer could not experience the single component but the whole vehicle; moreover the consumer could be even represented by the different companies depending on the point of view of the study (i.e. the car manufacturer is consumer, or client, of Magneti Marelli).

Product system

For the time being, there is no consensus on how to properly define the product system in the LCSA since the adoption of a technology-oriented approach, typical of LCA where the product system is made of several separated technological units positioned throughout the product life cycle, could be not appropriate for the social part.

Therefore the product system of the knuckle is presented according to a technology-oriented method, which could help in the LCA and LCC data gathering, and an organization-oriented approach that will be followed for the S-LCA data gathering (Figure 52). The product at hand is a specific component whose value chain is well defined, therefore specific data, especially regarding the social part, were collected from the specific companies involved in the production stage. As for the raw material supply, fuel production and EOL treatments specific companies were not involved since it was difficult to identify them.

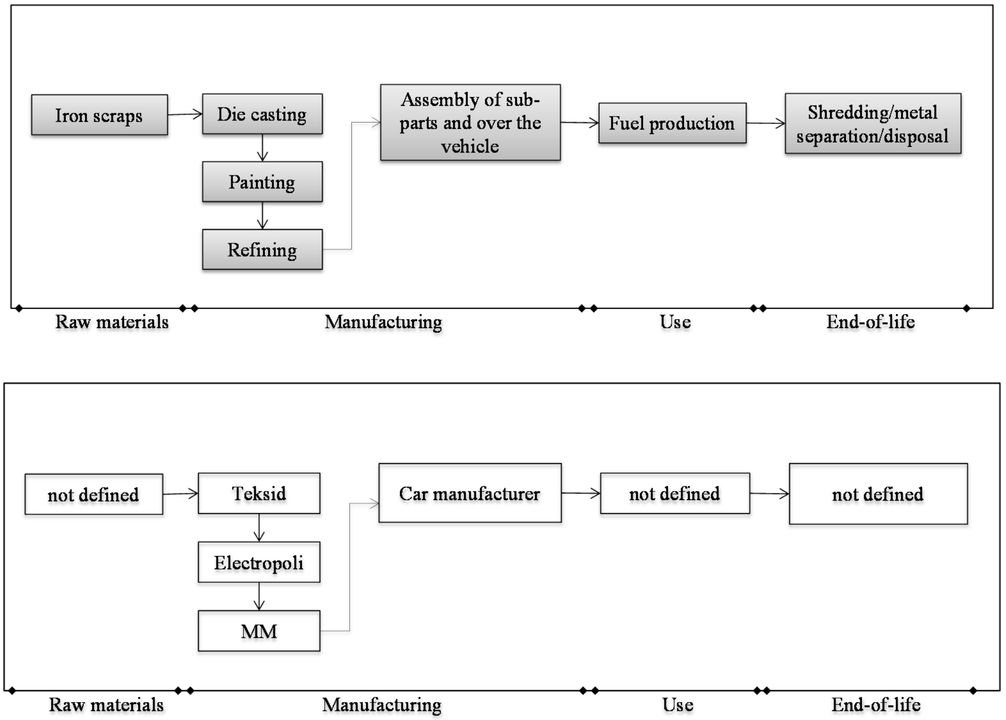


Figure 52 Product system of the knuckle: technology oriented (above) and organization-oriented (below)

System boundaries

The system boundaries are defined taking into account the car manufacturer perspective and the given product (a component of a vehicle system). They are depicted according to the double-layer approach described in chapter 5. In particular the physic layer identifies the processes included in the analysis, whereas the effect layer provides the stakeholder groups taken into account along the product life cycle.

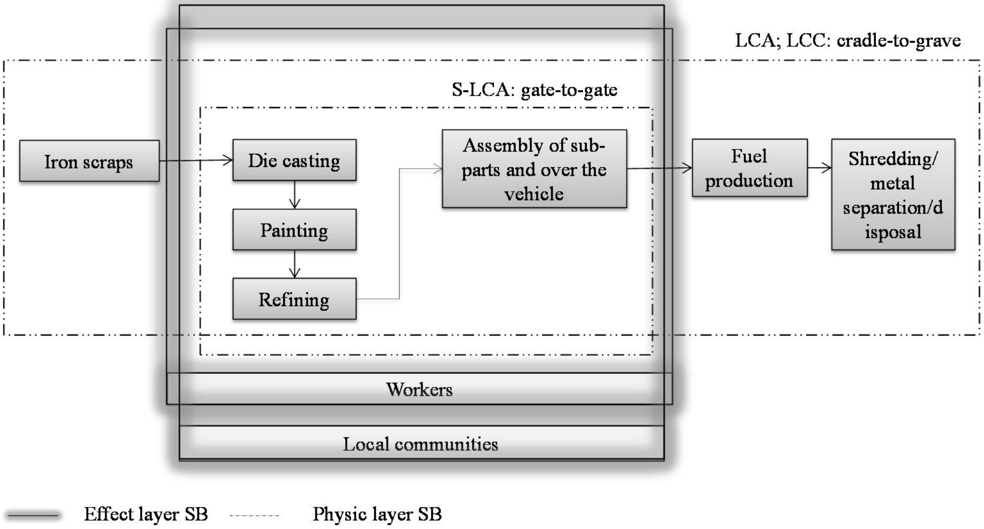


Figure 53 System boundaries of the knuckle life cycle

As it can be observed, the system boundaries are not the same for the LCA, LCC and S-LCA. The main reason for that is the object of the analysis (one component) which can be hardly related to specific social issues in the use stage since stakeholders are mainly involved in the use of the whole vehicle. The application of method for the allocation of social performances of the vehicle to the single component were not analysed in this study. Allocation according to the mass was done for the LCA and LCC, therefore the use stage was included in these two assessments.

Overall, the principle of system boundaries equivalence based on relevance for each assessment can be considered guaranteed.

As for the effect layer, it includes two stakeholder groups, workers and local communities, which are monitored especially regarding the manufacturing stage. More details are discussed in the following paragraph.

Stakeholder selection

According to the answers provided by the main companies, the most important stakeholder groups are: employees, suppliers, customers and communities.

Due to the low experience concerning social assessment and the related indicators, it was decided to focus on the workers and local communities. As for the consumer, it was decide to not include this group since the consumer do not experience the single component but the whole vehicle therefore this group was not relevant for the given application.

Functional unit

In this application the functional unit is defined as one steering knuckle to be mounted on the suspension system of a diesel turbo charged vehicle, with a life-distance of 150,000 km for 10 years. The function of the component is to connect the tie bar, wheel and suspension system (shock absorber and coil spring) of a vehicle with a curb weight of 1,360 kg (C class).

LCA and LCC results are presenting with reference to this functional unit, also for the S-LCA an attempt is done by applying the social impact assessment type I promoted by Roundtable for Product Social Impact Assessment (PRé Sustainability 2014). This is better described in the paragraph 0. The utility and suitability of the functional unit in the LCSA will be discussed in the results interpretation.

7.1.3. Inventory

LCA inventory

The manufacturing stage comprises three main steps: die casting, painting and refining. The refining process consists in machining, washing and deburring; the scraps produced are considered valuable material so it is treated by means of specific machine to produce briquette which then send to other plant to be recycled. In this study only the electricity for the briquetting process is included, whereas the briquette flow is out of system boundaries. These manufacturing processes were modelled by means of primary data reported in Table 42.

Table 42 LCA inventory of knuckle manufacturing processes (pd = primary data)

Flows	Process	Unit	Quantity
Die Casting			
---	DE: Cast iron part (automotive)	kg	6.43
Painting (pd)			
- Electricity	PL: Electricity grid mix 1kV-60kV	MJ	1.55
- Methane	DE: Methane	kg	0.0706
- Water	EU-27: Process water	kg	7.4
- Paint	DE: Coating electrodeposition	kg	0.015
- Pre-treatment chemicals	DE: Pre-treatment chemical (degreasing, phosphating)	kg	0.014
- Wastewater	EU27: Wastewater treatment (contains low organic load)	kg	7.41
Refining (pd)			
- Painted knuckle			6.43
- Electricity	PL: Electricity grid mix 1kV-60kV	MJ	7.6
- Compressed air	GLO: Compressed air 7 bar	Nm3	0.362
- Water	EU27: Tap water	kg	0.577
- Lubricant oil	EU27: Lubricants at refinery	kg	0.001
- Briquette	PL: Electricity grid mix 1kV-60kV	kg	1.29
- Wastewater	EU27: Wastewater treatment (contains low organic load)	kg	0.079
- Refined knuckle	---	kg	5.14

Data concerning the assembly stage were elaborated by the car manufacturer internally, and the information were provided as LCIA results. The use stage was modelled according to the formula reported in Annex A, the technical data of the reference vehicle are listed in Table 43.

Table 43 Technical data referring to vehicle model equipped by the knuckle

Data	**Unit**	**Quantity**
Vehicle model:	-	Diesel turbo charged 1995 cc, 110kW
Vehicle mass:	kg	1425
Emission stage (e.g. EURO5):	-	EURO5
Vehicle fuel consumption (mixed urban-extra):	l/100km	4.3
CO_2 emissions:	g/km	114
FRV value:	l/100 km×100 kg	0.12

The transport segments included in the analysis are representative of the real supply chain taking into a general site within Polish borders for the material supply and the real distances between manufacturing plant sites and assembly plant site (Table 44). The EOL stage was modelled by considering shredding process followed by metal recycling; the GaBi processes were used.

Table 44 Transport segments of knuckle case study (*GaBi dataset)

Segment	**Means of transport**	**Distance (km)**
Transport of raw material to die casting plant	Truck (30-40 t gross weight; 20-26 t payload capacity)*	50
Transport from die casting to painting plant	Truck (30-40 t gross weight; 27 t payload capacity)*	23
Transport from painting to refining plant	Truck (30-40 t gross weight; 20-26 t payload capacity)*	1
Transport from refining to assembly plant	Truck (30-40 t gross weight; 28-32 t payload capacity)*	747

LCC inventory

Table 45 LCC inventory of knuckle case study

Life cycle stages	Cost item	Unit	Value	Source
Part acquisition and transportation	Knuckle painted	€/FU	9.05	Primary data
	Transports from supplier's plant to MM plant	€/FU	0.01	Primary data
Refining	Labour cost	€/FU	0.43	Primary data
	Direct overhead (consumable materials + handling + utilities)	€/FU	1.43	Primary data
	Indirect overhead costs (MOI cost + fixed cost)	€/FU	0.57	Primary data
	Depreciation	€/FU	0.89	Primary data
	Maintenance and repairs costs (maintenance service + spare parts)	€/FU	0.16	Primary data
	Others (warranties, insurance, etc.)	€/FU	0.01	Primary data
Assembly	Cycle time	h/FU	0.045	Primary data
	Hourly labour cost	€/h	38	(Eurostat 2016b)
Use stage	Diesel	€/litre	1.13	(Eurostat 2016a)
	Fuel consumption (150,000 life span)	kg/FU	10.30	Calculated
EOL	Electricity consumption	kWh/ton	40	Primary data
	Electricity	€/kWh	0.12	(Eurostat 2016a)
	Spare parts	€/ton	3.00	Primary data

S-LCA data inventory

The data inventory has been developed according to the quantitative approach, proposed in the Handbook for Product Social Impact Assessment, which uses only numerical data measured as performance indicators, grouped into several social topics. Each social topic is represented by one or two performance indicators. The quantitative indicators are in two forms: absolute numbers (e.g. number of actions) or percentages (e.g. % of workers) (Table 46).

Table 46 Stakeholder groups, social issues and performance indicators of the quantitative approach (PRé Sustainability 2014) (Benefit = the highest is the positive; Cost = the lowest is the positive)

	Social topics	**Performance Indicators**	**Unit**	**Type**
Workers	Health and safety	Number of hours of health & safety training given during the reporting period.	hours	Benefit
		Average number of incidents during the reporting period.	Number	Cost
	Wages	Percentage of workers whose wages meet at least the legal or industry minimum wage and their provision fully complies with all applicable laws.	%	Benefit
		Percentage of workers who are paid a living wage.	%	Benefit
	Social benefits	Percentage of workers whose social benefits meet at least legal or industry minimum standards and their provision fully complies with all applicable laws.	%	Benefit
	Working hours	Percentage of workers who exceeded 48 hours of work per week regularly during the reporting period.	%	Cost
	Child labour	Number of hours of child labour identified during the reporting period.	Hours	Benefit
		Number of actions during the reporting period targeting business partners to raise awareness of the issue of child labour.	Actions	Cost
	Forced labour	Number of hours of forced labour identified during the reporting period.	Hours	Benefit
		Number of actions during the reporting period targeting business partners to raise awareness of the issue of forced labour.	Actions	Cost
	Discrimination	Number of complaints identified during the reporting period related with discrimination.	Complaints	Benefit
		Number of actions taken during the reporting period to increase staff diversity and/or promote equal opportunities.	Actions	Cost

	Social topics	**Performance Indicators**	**Unit**	**Type**
Workers	Freedom of association and collective bargaining	Percentage of workers identified during the reporting period who are members of associations able to organise themselves and/or bargain collectively.	%	Benefit
	Employment relationship	Percentage of workers who have documented employment conditions.	%	Benefit
	Training and education	Number of hours of training per employee during the reporting period.	Hours	Benefit
	Work-life balance	Percentage of workers with direct family responsibilities who were eligible for maternity protection, or to take maternity, parental, or compassionate leave during the reporting period.	%	Benefit
	Job satisfaction and engagement	Percentage of workers who participated in a job satisfaction and engagement survey during the reporting period.	%	Benefit
		Worker turnover rate during the reporting period.	%	Cost
Consumers	Health and safety	Number of claims acknowledged by a certification or accreditation body that the product contributes to a higher level of consumer health or safety.	Claims	Benefit
		Number of complaints identified during the reporting period related to consumer health and safety.	Complaints	Cost
	Experienced well-being	Composite measure of experienced well-being (1 to 10)	Absolute metric	Benefit
Local communities	Health and safety	Number of programmes during the reporting period to enhance community health and safety.	Programmes	Benefit
		Number of adverse impacts on community health or safety identified during the reporting period.	Adverse impacts	Cost
	Access to tangible resources	Number of programmes during the reporting period to enhance community access to tangible resources or infrastructure.	Programmes	Benefit
		Number of adverse impacts on community access to tangible resources or infrastructure during the reporting period.	Adverse impacts	Cost

	Social topics	Performance Indicators	Unit	Type
Local communities	Local capacity building	Number of programs targeting capacity building in the community during the reporting period.	Programmes	Benefit
		Number of people in the community benefitting from capacity building programmes during the reporting period.	Persons	Benefit
	Community engagement	Number of programmes or events targeting community engagement during the reporting period.	Programmes	Benefit
	Employment	Number of new jobs created during the reporting period.	New jobs	Benefit
		Number of jobs lost during the reporting period.	Jobs lost	Cost

The data inventory includes three main steps, listed in Figure 54: first data are collected for each life cycle stage (LCS_i indicator), then data need to be allocated to the single product (LCS_i allocated indicator) and finally the allocated values for each life cycle stage are summed up to obtain the aggregated value of the indicator along the product life cycle (PLC indicator). PLC indicator values are then elaborated by means of the impact assessment method proposed within the Roundtable (described in the following paragraph).

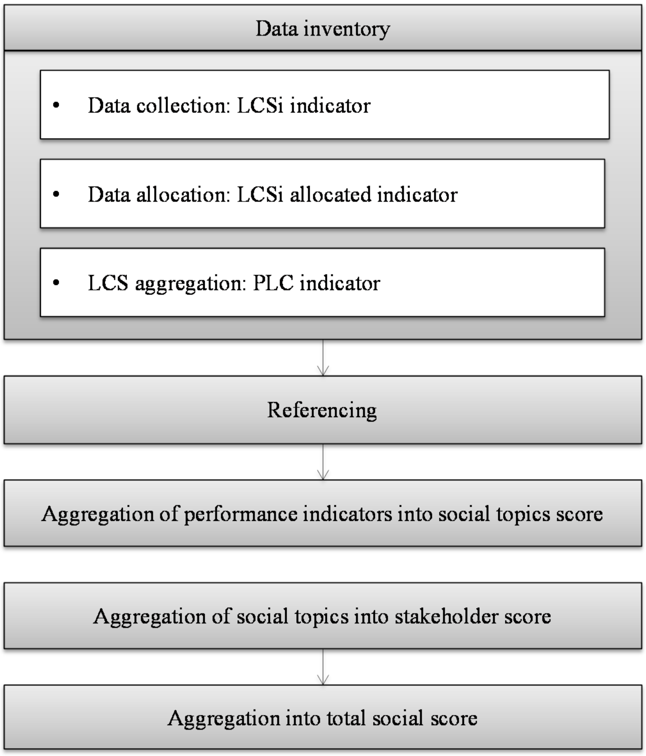


Figure 54 Procedure for collecting and processing data for the S-LCA according the Handbook (PRé Sustainability 2014)

In this specific application, data collection has involved four companies dealing with the manufacturing stage of the knuckle, in particular: die casting, painting, refining and assembly processes. Those are developed in four different plants so the LCS indicators i are related to those sites, and the data collection was developed by means of the questionnaire provided by the Roundtable ("Quantitative questionnaire") (PRé Sustainability 2015).

S-LCA data allocation

As for the S-LCA, data have been collected with reference to the plant where the process is carried out. All of the assessed plants are not exclusively dedicated to the knuckle but comprises also other business lines. Consequently, the data collected at plant level have to be allocated to the business line and the single product to be assessed.

The allocation is done according to the following formula:

$$LCSi_{\,indicator\ product\ allocated} = LCSi_{\,indicator\ site\ level} \times allocation\ factor \tag{28}$$

Where $LCSi_{\,indicator\ site\ level}$ is the performance indicator value at the life cycle stage i and the allocation factor is based on the working hours. The "Quantitative questionnaire" provided by the Roundtable suggests the following parameters to be collected for the allocation factor (Table 47). By means of these data, it is possible to distinguish between numbers of workers employed in the specific business line and the total number working in the plant.

Table 47 Parameters for the allocation factor calculation

ID	**Parameter**	**Unit**
P site	Number of employees at the site	Employees at site
P production line	Number of employees working at the specific production line	Employees at production line
N site	Total production at site level	ton; unit; etc.
N production line	Total production of the product assessed	ton; unit; etc.
h empl. site	Average number of working hours per employee per week at the site	Hours
h empl. production line	Average number of working hours per employee per week at the production line	Hours

Then the worksheet ("Quantitative questionnaire") calculates the allocation factor as the ratio between hours worked to produce one unit of any product at the site and hours worked to produce one unit of the product assessed.

$$Allocation\ factor = \frac{hours\ per\ product\ per\ site}{hours\ per\ product\ per\ production\ line} =$$

$$= \frac{P_{production\ line} \times h_{empl.production\ line} \times 52\ weeks \Big/ N_{production\ line}}{P_{site} \times h_{empl.site} \times 52\ weeks \Big/ N_{site}} \qquad (29)$$

By applying it to the given case study, this formula was found inconsistent since it does not guarantee appropriate allocation factors, in fact the values were revealed higher than 1.

In this specific application, an alternative formula for the allocation factor was used:

$$Allocation\ factor\ 1 = \frac{P_{site} \times h_{empl.site} \times 52 weeks}{P_{production\ line} \times h_{empl.production\ line} \times 52 week} \qquad (30)$$

It was possible to collect these required parameters concerning three plants, whereas for the car manufacturer plant different information were available (Table 48), therefore the allocation factor was calculated according to a different formula where the number of working hours needed to produce one unit of product at the *i* life cycle stage was an information directly provided by the Company:

$$Allocation\ factor\ 2 = \frac{LCSi_{hours} \times P_{production\ line}}{\text{number of working hours per year at the site}} \qquad (31)$$

Where the $LCSi_{hours}$ is the worked hours per product per production line calculated with the formula (2). This difference is mainly guided by the relevance of the assessed product (in terms of process duration), with respect to the whole activity of the plant. For instance, in the car manufacturer plant the process for knuckle assembly is extremely small if compared with other activities developed for the vehicle assembly, therefore it is difficult to identify number of employees specifically dedicated to this process phase. This is also demonstrated by the low allocation factor of the car manufacturer site if compared with those of the other plants.

Table 48 Data for allocation factor of Company A, Company B, Magneti Marelli and the car manufacturer

Parameter	Unit	Company A	Company B	Magneti Marelli	Car manufacturer
Number of employees at the site	employees at site	547	473	399	confidential
Number of employees working at the specific production line	employees at LCS	100	64	35	confidential
Total production at site level	Mg	61 598	47 498 633	7 357 959.5	confidential
Total production of the product assessed	Mg	3 173.8	489 025	490 063	confidential
Average number of working hours per employee per week at the site	hours	40	40	35	confidential
Average number of working hours per employee per week at the production line	hours	40	40	n.a	confidential
Allocation factor		0.18	0.14	0.09	0.018

In Annex D the performance indicator values, allocated to the product, are reported for each process/plant.

S-LCA data aggregation along product life cycle

The handbook provides two formula for the aggregation of LCSi $_{\text{indicator product allocated}}$ values to the PLC values (product life cycle), depending on the form of the performance indicator.

When the indicator is an absolute number the aggregation should be done according to the following formula:

$$PLC_{indicator} = \sum_{i} \left(LCSi_{indicator\ product\ allocated} \times LCSi_{hours} \right) \tag{32}$$

When the indicator is a percentage the aggregation is done according to the following formula:

$$PLC_{indicator} = \frac{\sum_i LCSi_{indicator\ product\ allocated}}{\sum_i LCSi_{hours}} \tag{33}$$

Values of $LCSi_{hours}$ are listed in Table 49; the total worked hours of one unit of knuckle along it life cycle is 0.87. The PLC indicator values are listed in Annex D.

Table 49 Values of hours worked to produce one unit of the product assessed (LCSi $_{\text{hours}}$)

	Suppliers		**Manufacturing**		**Use stage**	**EOL**
	Life Cycle Stage 1	**Life Cycle Stage 2**	**Life Cycle Stage 3**	**Life Cycle Stage 4**	**Life Cycle Stage 5**	**Life Cycle Stage 6**
Company name	Company A	Company B	Magneti Marelli	Car manufacturer	---	---
LCSi hours	0.42	0.27	0.13	0.05	---	---

7.1.4. Impact assessment

The environmental assessment is carried out according to the eleven impact categories of the CML 2001 method (Guinee et al., 2002): Global Warming Potential (100 years) (GWP), Abiotic Depletion Potential elements ($ADP_{elements}$), Marine aquatic Ecotoxicity Potential (MAETP), Ozone Depletion Potential (ODP), Eutrophication Potential (EP), Acidification Potential (AP), Human Toxicity Potential (HTTP), Photochemical Ozone Creation Potential (POCP), Terrestrial Ecotoxicity Potenital (TEP) and Fresh-water Aquatic Ecotoxicity Potential (FAEP). The Primary Energy Demand (PED) is also included.

The life cycle cost has been calculated using a steady-state model (Hunkeler et al. 2008); thus the use stage value is assumed as constant on time (a discount rate of 0).

The S-LCA involves performance indicators; according to the Roundtable for Product Social Metrics initiative coordinated by PRé Consultant the indicator values are first compared with reference values and then they are elaborated by means of weighting procedure to obtain social topics score, stakeholders score and total social score (Figure 54). For this reason it can be classified as method type I according to the social assessment method categories proposed by S-LCA guidelines (Parent et al. 2010; Garrido et al. 2016).

LCIA

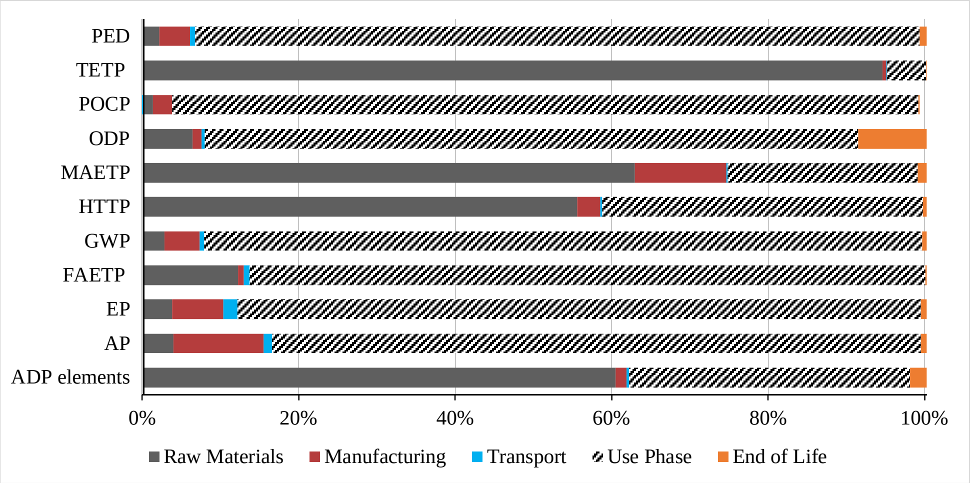


Figure 55 Environmental impact of knuckle case study: life cycle stages' contributions

Table 50 LCIA results of knuckle case study

	Unit	Raw Materials	Manufacturing	Transport	Use stage	EOL	Total
ADP$_{el.}$	kg Sb-eq/FU	3.63E-06	8.38E-08	1.81E-08	2.16E-06	1.28E-07	6.01E-06
AP	kg SO_2-eq/FU	2.34E-03	7.25E-03	6.60E-04	5.20E-02	4.37E-04	6.27E-02
EP	kg Phosphate-eq/FU	3.10E-04	5.53E-04	1.53E-04	7.44E-03	5.87E-05	8.52E-03
FAETP	kg DCB-eq/FU	2.71E-02	1.61E-03	1.59E-03	1.94E-01	3.84E-04	2.25E-01
GWP	kg CO_2-eq/FU	1.26E+00	2.15E+00	2.72E-01	4.41E+01	2.66E-01	4.81E+01
HTP	kg DCB-eq/FU	1.63E+00	8.71E-02	6.65E-03	1.21E+00	1.31E-02	2.95E+00
MAETP	kg DCB-eq/FU	1.35E+03	2.52E+02	3.51E+00	5.24E+02	2.50E+01	2.16E+03
ODP	kg R11-eq/FU	2.00E-11	3.78E-12	1.25E-12	2.69E-10	2.81E-11	3.22E-10
POCP	kg Ethene-eq/FU	2.31E-04	5.03E-04	-1.84E-04	1.97E-02	3.50E-05	2.03E-02
TETP	kg DCB-eq/FU	3.86E-01	1.79E-03	6.16E-04	2.04E-02	1.69E-04	4.10E-01
PED	MJ/FU	1.20E+01	2.49E+01	4.24E+00	5.83E+02	5.43E+00	6.29E+02

LCC – costs aggregation analysis

Table 51 LCC results of knuckle case study

Life cycle stages	Unit	Value
Part acquisition and transportation	€	9.05
Refining and assembly	€	5.21
Use stage	€	13.70
EOL	€	0.04
Life Cycle Costing	**€**	**28.00**

Applying the social assessment method type I of the Roundtable for Product Social Metrics initiative

The social assessment is carried out following the procedure proposed by the Roundtable for Product Social Metrics initiative coordinated by PRé Consultant (Figure 54).

The procedure comprises a referencing step where PLC indicators (aggregated value of the indicator along the life cycle) are compared to reference values in order to evaluate the relative positive or negative performance of the product in the social impact assessment. In particular, the performance value (PV) is calculated for each indicator comparing the PLC indicator with the reference value (RV) of the indicator.

Due to the different types of quantitative indicators (benefit= higher is better; cost= lower is better), different reference could be applied. Some indicators, like the ones related to child and forced labour a common ethical reference may be applied, while for other indicators, such as the number of hours of health and safety training the worst case scenario as a minimum standard value can be applied. This is concept is necessary as far as no definitive standard exists.

Depending on the indicator type (benefit or cost) and the reference scenario, three referencing process may be applied:

- Referencing process 1 → PV = PLC indicator – RV;
- Referencing process 2 → PV = RV – PLC indicator;
- Referencing process 3 → PV = PLC indicator.

An attempt was done to identify reference values specifically targeted to the automotive sector (i.e. statistic values, best performances of the sector, normative limit). It was not possible to find out that because these issues could be measured by not the same indicators and because it is generally difficult, for the moment to find out this kind of statistic or directive laws. Therefore, it was decided to apply the reference value of the Handbook (Table 52).

Table 52 Reference values and referencing process for each quantitative indicator

	Performance indicators	**Unit**	**RV**	**Reference scenario**	**Referencing process**
Workers	Number of hours of health and safety training per worker given during the reporting period.	hours	1	worst	1
	Average rate of incidents during the reporting period.	number	0	ideal	2
	Percentage of workers whose wages meet at least legal or industry minimum standards and their provision fully complies with all applicable laws.	%	100%	ideal	3
	Percentage of workers who are paid a living wage.	%	100%	ideal	3
	Percentage of workers whose social benefits meet at least legal or industry minimum standards and their provision fully complies with all applicable laws.	%	100%	ideal	3
	Percentage of workers who exceeded 48 hours of work per week regularly during the reporting period.	%	0%	ideal	2

	Performance indicators	**Unit**	**RV**	**Reference scenario**	**Referencing process**
Workers	Number of hours of child labour identified during the reporting period.	hours	0	ideal	2
	Number of actions during the reporting period targeting business partners to raise awareness of the issue of child labour.	actions	1	worst	1
	Number of hours of forced labour identified during the reporting period.	hours	0	ideal	2
	Number of actions during the reporting period targeting business partners to raise awareness of the issue of forced labour.	actions	1	worst	1
	Number of complaints identified during the reporting period related to discrimination.	complaints	0	ideal	2
	Number of actions taken during the reporting period to increase staff diversity and/or promote equal opportunities.	actions	1	worst	1
	Percentage of workers identified during the reporting period who are members of associations able to organise themselves and/or bargain collectively.	%	100%	ideal	3
	Percentage of workers who have documented employment conditions.	%	100%	ideal	3
	Numbers of hours of training per employee during the reporting period.	hours	1	worst	1
	Percentage of workers with direct family responsibilities who were eligible for maternity protection, or to take maternity, parental or compassionate leave during the reporting period.	%	100%	ideal	3
	Percentage of workers who participated in a job satisfaction and engagement survey during the reporting period.	%	100%	ideal	3
	Worker turnover rate during the reporting period.	%	0%	ideal	2

	Performance indicators	**Unit**	**RV**	**Reference scenario**	**Referencing process**
Local communities	Number of programmes during the reporting period to enhance community health or safety.	programmes	1	worst	1
	Number of adverse impacts on community health or safety identified during the reporting period.	adverse impacts	0	ideal	2
	Number of programmes during the reporting period to enhance community access to tangible resources or infrastructure.	programmes	1	worst	1
	Number of adverse impacts on community access to tangible resources or infrastructure during the reporting period.	adverse impacts	0	ideal	2
	Number of programmes targeting capacity building in the community during the reporting period.	programmes	1	worst	1
	Number of people in the community benefitting from capacity building programmes during the reporting period.	persons	1	worst	1
	Number of programmes or events targeting community engagement during the reporting period.	programmes	1	worst	1
	Number of new jobs created during the reporting period.	new jobs	1	worst	1
	Number of jobs lost during the reporting period.	jobs lost	0	ideal	2

The calculated performance values are listed in Table 53; by using the aforementioned referencing process the PV values can be interpreted as following:

- PV=0 (referencing process 1 and 2) or PV=RV (referencing process 3) means the target or minimum scenario has been reached;
- PV>0, the indicator demonstrates positive performance;
- PV<0, the indicator demonstrates negative performance.

Table 53 S-LCA results: performance values of knuckle case study

Performance indicators	**unit**	**Type**	**RV**	**PV**	**Performance evaluation**
Number of hours of health and safety training per worker given during the reporting period.	hours	benefit	1	-0.048	negative performance
Average rate of incidents during the reporting period.	number	cost	0	-0.900	negative performance
Percentage of workers whose wages meet at least legal or industry minimum standards and their provision fully complies with all applicable laws.	%	benefit	100%	51.99%	positive performance
Percentage of workers who are paid a living wage.	%	benefit	100%	5.21%	positive performance
Percentage of workers whose social benefits meet at least legal or industry minimum standards and their provision fully complies with all applicable laws.	%	benefit	100%	51.53%	positive performance
Percentage of workers who exceeded 48 hours of work per week regularly during the reporting period.	%	cost	0%	0.00%	target or minimum scenario has been reached
Number of hours of child labour identified during the reporting period.	hours	cost	0	0.000	target or minimum scenario has been reached
Number of actions during the reporting period targeting business partners to raise awareness of the issue of child labour.	actions	benefit	1	-0.999	negative performance
Number of hours of forced labour identified during the reporting period.	hours	cost	0	0.000	target or minimum scenario has been reached
Number of actions during the reporting period targeting business partners to raise awareness of the issue of forced labour.	actions	benefit	1	-0.999	negative performance
Number of complaints identified during the reporting period related to discrimination.	complaints	cost	0	0.000	target or minimum scenario has been reached
Number of actions taken during the reporting period to increase staff diversity and/or promote equal opportunities.	actions	benefit	1	-0.887	negative performance

Performance indicators	**unit**	**Type**	**RV**	**PV**	**Performance evaluation**
Percentage of workers identified during the reporting period who are members of associations able to organise themselves and/or bargain collectively.	%	benefit	100%	20.59%	positive performance
Percentage of workers who have documented employment conditions.	%	benefit	100%	100.00%	target or minimum scenario has been reached
Numbers of hours of training per employee during the reporting period.	hours	benefit	1	-0.345	negative performance
Percentage of workers with direct family responsibilities who were eligible for maternity protection, or to take maternity, parental or compassionate leave during the reporting period.	%	benefit	100%	11.54%	positive performance
Percentage of workers who participated in a job satisfaction and engagement survey during the reporting period.	%	benefit	100%	40.13%	positive performance
Worker turnover rate during the reporting period.	%	cost	0%	-1.09%	negative performance
Number of programmes during the reporting period to enhance community health or safety.	programmes	benefit	1	-0.922	negative performance
Number of adverse impacts on community health or safety identified during the reporting period.	adverse impacts	cost	0	-0.001	negative performance
Number of programmes during the reporting period to enhance community access to tangible resources or infrastructure.	programmes	benefit	1	-	
Number of adverse impacts on community access to tangible resources or infrastructure during the reporting period.	adverse impacts	cost	0	-	
Number of programmes targeting capacity building in the community during the reporting period.	programmes	benefit	1	-	
Number of people in the community benefitting from capacity building programmes during the reporting period.	persons	benefit	1	-	
Number of programmes or events targeting community engagement during the reporting period.	programmes	benefit	1	-0.359	negative performance
Number of new jobs created during the reporting period.	new jobs	benefit	1	-0.669	negative performance
Number of jobs lost during the reporting period.	jobs lost	cost	0	-0.074	negative performance

The following step of the method is the calculation of the dimensionless indicators scores; this is necessary for the aggregation of the performance indicators values to the social topic score and may be relevant when two or more products are compared. In this application this step was not developed, being an absolute assessment and not a comparison. Also the other steps proposed by the Handbook – stakeholder score and social score - where not possible for the same reason.

7.1.5.Results interpretation and discussions

Interpreting the results from LCA, LCC and S-LCA in a combined way was not possible in this application since it involves an absolute assessment and all the method currently available may be applied when product need to be compared. As a consequence, the LCSA results, reported in Table 54, can be discussed indicator by indicator, or within each sustainability area with the aim of identifying the hotspot in a sustainable perspective.

The 43 indicators cannot be directly compared because they have different units, moreover they represent different level of information. In the impact pathway, they place in the different position; LCC result is mainly a performance or even an inventory information, whereas LCA results are impact (mid-point) and S-LCA are performance.

Table 54 LCSA results of knuckle case study

	Indicator	**ID**	**Unit**	**Knuckle**
LCC	Raw material cost	LCC_1	€/FU	9.050
	Production cost	LCC_2	€/FU	3.690
	Use cost	LCC_3	€/FU	15.24
	EOL	LCC_4	€/FU	0.030
LCA	GWP	LCA_1	kg $CO_{2\text{-eq}}$/FU	4.81E+01
	AP	LCA_2	kg $SO_{2\text{-eq}}$/FU	6.27E-02
	$ADP_{el.}$	LCA_3	kg $Sb_{\text{-eq}}$/FU	6.01E-06
	PED	LCA_4	MJ/FU	6.29E+02
	HTP	LCA_5	kg $DCB_{\text{-eq}}$/FU	2.95E+00
	FAETP	LCA_6	kg $DCB_{\text{-eq}}$/FU	2.25E-01
	MAETP	LCA_7	kg $DCB_{\text{-eq}}$/FU	2.16E+03
	TETP	LCA_8	kg $DCB_{\text{-eq}}$/FU	4.10E-01
	ODP	LCA_9	kg $R11_{\text{-eq}}$/FU	3.22E-10
	EP	LCA_{10}	kg $Phosphate_{\text{-eq}}$/FU	8.52E-03
	POCP	LCA_{11}	kg $Ethene_{\text{-eq}}$/FU	2.03E-02

	Indicator	**ID**	**Unit**	**Knuckle**
S-LCA	Health and Safety workers	S-LCA$_{1}$	h/FU	9.52E-01
		S-LCA$_{2}$	number/FU	9.00E-01
	Wages	S-LCA$_{3}$	%	51.99%
		S-LCA$_{4}$	%	5.21%
	Social benefits	S-LCA$_{5}$	%	51.53%
	Working hours	S-LCA$_{6}$	%	0.00%
	Child labour	S-LCA$_{7}$	h/FU	0.00E+00
		S-LCA$_{8}$	actions/FU	8.09E-04
	Forced labour	S-LCA$_{9}$	h/FU	0.00E+00
		S-LCA$_{10}$	actions/FU	8.09E-04
	Discrimination	S-LCA$_{11}$	complaints/FU	0.00E+00
		S-LCA$_{12}$	actions/FU	1.13E-01
	Freedom of association	S-LCA$_{19}$	%	20.59%
	Employment relationship	S-LCA$_{24}$	%	100.00%
	Training and education	S-LCA$_{7}$	h/FU	6.55E-01
	Work-life balance	S-LCA$_{21}$	%	11.54%
	Job satisfaction	S-LCA$_{8}$	%	40.13%
		S-LCA$_{9}$	%	1.09%
	Health and safety local community	S-LCA$_{10}$	programmes/FU	7.78E-02
		S-LCA$_{11}$	adverse impacts/FU	8.09E-04
	Community engagement	S-LCA$_{12}$	programmes/FU	6.41E-01
	Employment local community	S-LCA$_{24}$	new jobs/FU	3.31E-01
		S-LCA$_{25}$	jobs lost/FU	7.37E-02

One of the main contribution of this application is the opportunity to develop a S-LCA by collecting primary data (site specific) of the manufacturing stage and test the method proposed by the Handbook for Product Social Impact Assessment.

In particular it gave the opportunity to test the list of social quantitative indicators, in terms of affordability and completeness, and apply the procedure to elaborate such data: allocation to functional unit, aggregation and referencing.

Selection and use of social indicators is claimed to be an important challenge for the S-LCA progress; for this reason Companies were involved in a process of critical discussion of indicators in terms of relevance/appropriateness, affordability/availability, understanding and completeness:

- Relevance:

  - Stakeholder ‘consumer’ is considered not relevant and, in some case, misleading since it is not clear the target for the given product;
  - ‘Health and safety’ for local communities is considered not relevant for the specific activities carried out by the specific plants.
- Affordability/availability:
  - Information about ‘Freedom of association and collective bargaining’ may be in some case not available due to privacy reasons;
  - Programmes specifically targeted to ‘Access to tangible resources’ and ‘Local capacity building’ are not easy to be measured since they could be generally mentioned as programmes regarding health and safety and community engagement;
  - Measures and declarations about ‘child labour’ and ‘discrimination’ could mainly regard material suppliers since the companies involved are all in a geographic region (Europe) where such social aspect is generally preserved by specific laws. However it was found difficult to provide specific declarations about such social issues for the suppliers. Indeed, these social topics could be generally managed at organization level instead of site level;
  - Information about ‘Access to tangible resources’ and ‘Local capacity building’ were not available.
- Understanding:
  - ‘Percentage of workers who exceeded 48 hours of work per week regularly during the reporting period.’ was found not clear in case of workers that don't have their over hours recorded due to their contract;
  - The indicator ‘Percentage of workers who have documented employment conditions.’ was found misleading as it was considered referring to ergonomical/safe assessment of the workbench/desk they work at;
  - ‘Percentage of workers who exceeded 48 hours of work per week regularly during the reporting period.’ was found too generic and not easy to answer to (“It could depend also on the line and model”).
  - How to interpret the ‘Percentage of workers who are paid a living wage’ was found ambiguous; overall it should be consider a benefit (higher is better).
- Regarding completeness, it was suggested to include also a ‘local employment’ indicators such as ‘Percentage of direct workforce hired locally (i.e. % of total payroll that goes to local workers) or ‘Percentage of supplies that are sourced locally’.

Along with indicators discussion, the companies were asked to provide examples of actions/programmers that they included in the questionnaire. In the following, a list is reported:

- Examples of ‘communities engagement’ actions: thesis and internship with the University, information campaign about waste selection in the schools, actions in the local orphanage, volunteering actions for donations collection (poor families, blankets and food for shelter), aid for employees' children (baby linen, outings to the cinema, cities, theatre, subsidies for school books, subsidy for holidays, subsidy for Santa Claus & Christmas), art competitions for children, allowance due to the difficult financial & life situation;

- Examples of 'discrimination' actions: age and gender diversity in employment, employment of disabled people, employment of foreigners (from Ukraine).

This was the first application of the quantitative approach, for this reason all the data elaboration (allocation, aggregation and referencing) were critically applied.

Overall it was found that when the plant, or even a production line, is intensely involved in the given product (i.e. Magneti Marelli plant) then it was possible to collect data for the allocation factor based on the worked hours proposed by the Handbook. When the processes regarding the assessed product represent a minor part of the overall activity at site (e.g. car manufacturer plant) then different information are available and so the allocation factor need to be calculated by means of an alternative formula. In this application an example of alternative calculation is provided by the formula (4), however other applications are needed to better analyse this aspect.

The LCSi indicators were aggregated to the PLC indicator values by means of different formula depending on the quantitative indicator form (absolute number vs. percentage). For those indicators measured as percentage the PLC value is a weighted average according to worked hours at each life cycle stage. Nevertheless, the analysis of the collected data suggested that there is not a mathematical limitation in applying the same formula also to the absolute numbers. When the weighted average is applied to all the indicators, different PLC values are obtained and in some case this could affect the following evaluations in a not negligible way. For this reason, more efforts may be dedicated to understand the different information that could be derived from these two different aggregation procedures.

The PLC values are compared with references and three different referencing processes are proposed by the Handbook depending on the indicator type and form. This step enhances the following interpretation of performance values (distance from the target).

Overall, it was not easy to interpret all the indicators due to the high number but also to their heterogeneity. They need to be analysed attentively since each one was referenced to a different conceptual scenario and so it was not easy to understand the positive or negative evaluation.

As an example, the indicators concerning the 'Wage' social topic resulted both as positive performance (PV>0), however they were found both far from reference (100%).

For those indicators measured as number of actions/programmes (e.g. 'Child labour' and 'Forced labour') the reference value is identified according to an ideal scenario where at least 1 action should be done. In this case the allocation of reference solution seems to be appropriate in order to guarantee a correct referencing process. The Handbook only mentions that 'reference value should be compatible' to units of the data collected, therefore it can be argued that the allocation process could be necessary also for the reference values. Indeed, the allocation of reference values was mentioned in the old version of the Handbook but it is not clear how it need to be developed. In this specific application, the reference values of those indicators was done by multiplying them with the worked hours along the product life cycle (0.87).

For those indicators whose reference value is zero (e.g. ‘Average rate of incidents during the reporting period’, ‘Number of adverse impacts on community health or safety identified during the reporting period’, ‘Number of jobs lost during the reporting period’) the allocation of the reference value is not possible.

In Annex D the comparison between referencing without allocating reference value and the case with allocated reference values. As it can be observed, the performance evaluation changes only for the first indicator, however the distance from the target generally decrease.

7.2. Case study 2: dashboard

This case study was developed in collaboration with Magneti Marelli® (hereafter MM) and regards the comparison of two design solutions for a panel dashboard. The first represents the current solution while the second applies an innovative material for lightweight purpose.

7.2.1.Product description

The dashboard is the panel, placed in front of the driver, supporting and housing all the instrumentation for the vehicle use (Figure 56). From an eco-design point of view the dashboard is an interesting part due to its mass and certain amount of plastic materials. This makes it particularly relevant even from an EOL perspective (De Medina 2006; Andriankaja et al. 2009) since, according to the European directive 2000/53/EC on End-of-Life-Vehicles (ELVs), it is actually a component candidate to be removed for recycling; however this is not always ensured due to technical problems (Berzi et al. 2013).

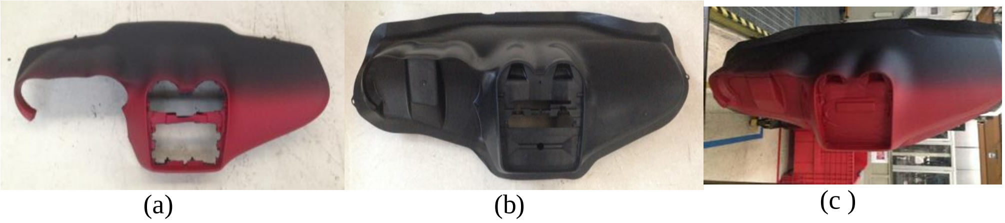

(a) (b) (c)

Figure 56 Automotive dashboard panel: Finalized component (a); Bottom layer (b); Upper mantle (c)

This study presents a comparison between two different composite-based solutions manufactured by MM. The first design uses talc filler-reinforced composite, while the second is based on the use of hollow glass micro-spheres with a lightweighting purpose.

The component at hand consists of three different polymeric material layers and the two solutions differ only in the bottom layer (Figure 56) which is made of polypropylene reinforced with 25% talc (PP 65.40 U) and PP reinforced with 23% Hollow Glass Microspheres (PP 23 HGM) in the standard and innovative design respectively (Table 55).

Table 55 Technical data dashboard design solutions (material quantities are referred to the finalized dashboard mass)

	Ref. solution - PP 65.40 U	**Light solution - PP 23 HGM**
Total mass [kg]	4.722	3.962 (-16%)
Bottom insert mass [kg]	2.49	1.712
Materials of bottom insert	PP reinforced with 25% talc	PP reinforced with 23% Hollow glass spheres
Other materials	Thermoplastic polyolefin TPO (1.12 kg) Isocyanate and polyol (1.122 kg)	Thermoplastic polyolefin TPO (1.12 kg) Isocyanate and polyol (1.122 kg)

The technical performances of the two alternative materials are reported in Table 56. One of the most important properties is the resilience since a proper shock load absorption due to dynamic stress (i.e. airbags opening) needs to be guaranteed. In this sense the talc is one the most commonly used filler and its mechanical performances are overall claimed in the literature (Luz et al. 2010). When compared with talc, the PP 23 HGM presents a lower value of Izod Impact strength (23 °C) (used as a reference test); nevertheless it proved to be within the limit of acceptance (Table 56). This also represents a limit for manufacturing scraps reuse as the shredding treatment entails the loss of the mechanical performance of the material, already at the limit of acceptance.

Table 56 Mechanical properties of materials

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

Despite the aforementioned criticalities, the PP 23 HGM can be considered a valuable material to be used for the component at hand; its low density, 30% below the PP 65.40 U, is one of the main reasons allowing a component weight reduction around 16%. Moreover, improvements in terms of thermal and sound insulation, and aesthetic features are expected. The talc substitution with the HGM does not entail changes in manufacturing processes, thus avoiding investment cost for new equipment. HGM are used in a variety of lightweight automotive applications (i.e. thermoplastics moulding composite, structural foam and body fillers, interior parts) (Yalcin and Amos 2015); in particular its use as thermoplastic filler (i.e. PP and PA) is suggested to produce lower-density injected moulding filled plastics without compromising physical properties (3M 2012). They are particularly used in filled polymer systems such as glass fibre and talc thermoplastics for their strength/weight optimum performance. They present several advantages: reduction and replacement of a certain amount of high density fillers resulting in weight reduction, without decreasing original mechanical properties; a faster cooling rate from the melt hence high productivity;

dimensional stability; increased stiffness and heat distortion resistance; reduced thermal conductivity and dielectric constant (Yalcin and Amos 2015). However, very little literature exists describing the eco-profile of HGM and its production process parameters (energy, chemicals) with the exception of patents reference (Kusaka et al. 2001; Tanaka et al. 2003).

7.2.2. Goal and Scope Definition

In this study, the main improvement drivers are weight reduction and the consequent fuel consumption saving for the whole vehicle. Improvements in the manufacturing stage are even expected, as described in the following paragraphs. As a consequence, the goal of this study is to analyse and compare the environmental, economic and social aspects during an early design phase of two alternative design solutions – a traditional one and an innovative one – for a dashboard produced by MM over its whole life cycle.

Perspective

For the case study at hand, the producer or company perspective is applied, in particular the perspective of Magneti Marelli, which is involved in the design and production stage of the final product. The consumer perspective is considered less interesting since the consumer could not experience the single component but the whole vehicle; moreover the consumer could be represented by the different companies depending on the point of view of the study. As far as eLCC is concerned, the 'hybrid perspective' (cfr. § chapter 4) is applied since costs directly supported by the manufacturer (production and transport) are summed to the cost for the user without any added value.

Product system

The product system of the dashboard is presented according to a technology-oriented method, which could help in the LCA and LCC data gathering, and an organization-oriented approach that will be followed for the S-LCA data gathering (Figure 57).

Material suppliers could not be involved in the analysis, whereas Magneti Marelli deals with all the manufacturing processes, from the semi-manufactured acquisition to the finalized component. The dashboard is then assembled on the vehicle in the FCA plant.

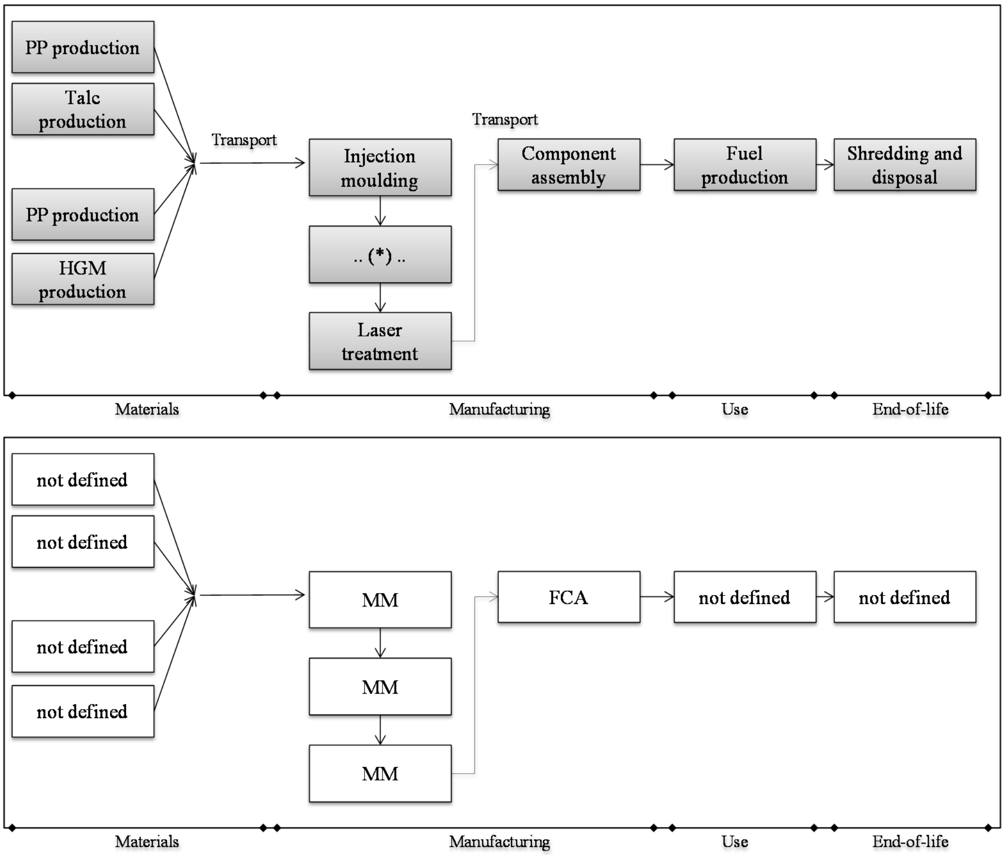


Figure 57 Product system of the dashboard: technology oriented (above) and organization-oriented (below) (* see Figure 59)

System boundaries

The double-layer system boundaries (cfr. § Chapter 5) are presented in Figure 58. They are different for the LCA, LCC and S-LCA but the principle of system boundaries equivalence based on relevance for each assessment has been adopted. Overall, the main aspects that guided the definition of system boundaries (both layers) are: i) the object of the analysis (one component), which can be hardly related to specific social issues in the use stage since stakeholders are mainly involved in the use of the whole vehicle; ii) data availability for the social assessment.

As for the effect layer, it includes two stakeholder groups, workers and local communities, which are monitored especially regarding the manufacturing stage. LCA and LCC physic layers include the following life cycle stages: materials production, component manufacturing, transports of semi-manufactured product (within the Company A, B and Magneti Marelli plants) and of the finalized dashboard to FCA plant for its assembly to the vehicle, use stage and End of Life treatments. Compounding and assembly processes have been neglected since they consist in low energy consumption and manual operations, respectively.

In this case study S-LCA has been focused on the production stage only since it was not possible to collect company data for other life cycle stages. In order to cover these stages, the PSILCA database (Ciroth and Eisfeldt 2016) was analysed; nevertheless it could not be used due to differences in terms of mapped social indicators (according to the available version 1, October 2015) which could not be summed and interpreted together with data collected for the other life cycle stages.

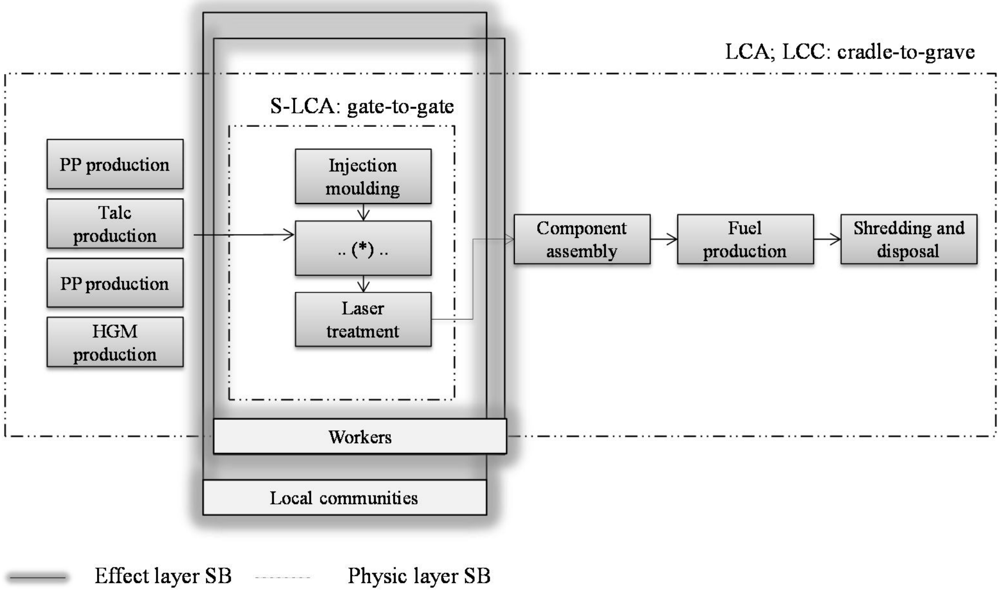


Figure 58 System boundaries of the knuckle life cycle for the LCSA study

Stakeholder selection

In this case study, the stakeholder selection was mainly guided by the “Quantitative questionnaire”, therefore workers and local communities were taken into account. For the consumer group the same reasoning of the Case study 1 were applied.

Functional unit

The Functional Unit (FU) is an automotive dashboard panel, supporting and housing all the instrumentation for the vehicle use, to be mounted on Alfa Romeo Mito 955 diesel engine, with a life-distance of 150,000 km for 10 years. It is considered the most important and complicated part of the automotive interior since it has to cover aesthetic, safety, rigidity and lightweight performances (Tian and Chen 2014).

7.2.3. Inventory

As previously mentioned, one of the main contribution of this case study is the data collection concerning production and manufacturing of the innovative material PP 23 HGM, which is currently not available in commercial databases. Information useful for the environmental and economic assessment was directly collected or retrieved from literature, whereas data for the social assessment were collected by means of the ‘Quantitative questionnaire’ proposed by the Roundtable for Product Social Impact Assessment (cfr. § 7.1.3).

LCA inventory

The material production stage encompasses raw material extraction and processing, whereas the matrix and fillers compounding process has been excluded from the analysis since its energy consumption is considered negligible from experts’ judgment if compared with raw materials processing. Table 57 lists materials quantities and database processes for each dashboard solution, according to the design data (Table 55).

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

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

So the HGM production process has been modelled by including the raw materials, according to the specific composition, and assuming the same energy consumption of the Pyrex process as the most similar among the processes available in the commercial database (Table 57). This means that the borosilicate process, retrieved from ecoinvent, has been modified by applying the specific raw materials involved in the HGM composition (Table 57).

Table 57 Inventory data for material production stage dashboard case study (*gross value, including the scraps produced during the manufacturing stage)

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

The manufacturing stage encompasses the processes depicted in Figure 59; first the lower insert is produced by means of injection moulding process then the upper part of the dashboard, the external visible layer, is manufactured via vacuum thermoforming process. The lower insert and the upper mantle are combined during the foaming process and their final shape is regulated by means of milling process; a final laser processing is then developed.

The manufacturing stage of the two solutions differs only in the shredding of injection moulding scraps (Figure 59). The material used in the traditional solution allows a reuse of the injection moulding scraps, after the shredding treatment; this is not possible for the innovative material whose mechanical properties decrease too much after shredding. The scraps flows stemmed from the other processes cannot be recycled and are disposed to landfill.

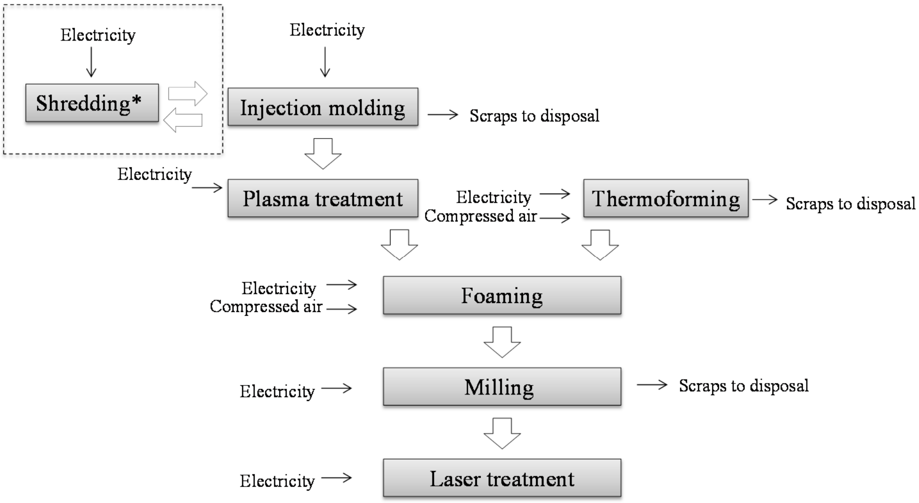


Figure 59 Manufacturing processes flow dashboard case study (*shredding only in the case of standard solution)

Data collection campaign was conducted on site during one eight hours shift; measurements were done every 15 minutes for each manufacturing machine and auxiliary facilities (air treatment, lightning, etc.). Energy and compressed air consumptions, and the scrap rate values are detailed in Table 58. The electricity country-mixes specific of the countries involved in the processes are used; the compressed air production process was taken from GaBi. As for the innovative solution, these values have been calculated according to the cycle time, measured during the prototype production (Table 58). However, due to the large number of prototypes produced within one shift, these values can be considered representative also of a mass customization process.

The cycle time of the injection moulding phase was measured for standard solution and during the testing phase of innovative solution; the latter was found 10% smaller (Table 58). The major fluidity of the innovative material - PP 23 HGM - compared to the standard one – PP 65.40 U – mostly influences the injection phase; in fact the lower thermal inertia of the glass microspheres compared to talc allows a faster cooling of the moulded component.

The use stage was modelled according to the formula reported in Annex A, the technical data of the reference vehicle are listed in Table 59.

The transport segments included in the analysis are representative of the real supply chain of the traditional and innovative solutions taking into account suppliers' sites, manufacturing plant site and assembly plant site (Table 60). Transports of raw materials have not been calculated as already included in the materials production dataset.

Table 58 Electricity consumption, compressed air consumption, scraps rate and cycle time of manufacturing processes of the two dashboard solutions

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

Table 59 Technical data referring to vehicle model equipped with the dashboard

Vehicle model Alfa Romeo Mito 1.6, Diesel (1,600 cm^3, 74 kW)	
Vehicle mass [kg]	1,355
Type of car	EURO 5
Cycle	Mixed driving cycle
Vehicle fuel consumption [l/100km]	8.1
CO_2 emissions [g/km]	125
Distance use [km]	150,000

Table 60 Transport segments dashboard case study (*GaBi dataset)

Segment	Means of transport	Distance (km)
PP from material supplier to material production site	Truck (30-40 t gross weight; 27 t payload capacity)*	983
HGM from material supplier to material production site		1,290
PP 65.40U from material supplier to manufacturing plant		982
PP 23 HGM from material production plant to manufacturing plant		420
Dashboard from manufacturing plant to assembly plant		40

Overall the dashboard is one of the components specifically mentioned to be separated according to the ELVs directive (EC 2000); as a matter of fact, its dismantling is currently impeded by three main aspects: i) it is difficult to remove; ii) is a labour intensive activity; iii) it is unlikely recyclable, since different incompatible polymeric families are generally involved, thus limiting the use of current mechanical methods for the material separation (Ragosta et al. 2001; Tharumarajah and Koltun 2010; Tian and Chen 2014).

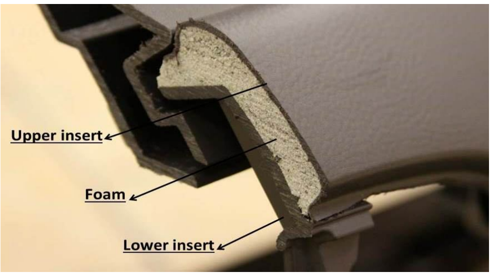


Figure 60 Dashboard section

In this sense, the use of the lighter material – PP 23 HGM – does not seem to provide relevant variations for the EOL stage: the three layers are not physically separable in both cases (Figure 60), and there are no current second uses for mixed granulate after mechanical treatments (Tian and Chen 2014). As a consequence significant changes (advantages or disadvantages) could not be expected by the lightweight solution, with the exception of a lower landfilled waste amount due to a lower quantity of involved materials. However this aspect is supposed to play a negligible role. For the above reasons the EOL stage of the dashboard includes the shredding treatment, assuming an electricity consumption of 95 kWh/ton (Tian and Chen 2014), followed by two alternative treatments: After Shredding Residues (ASR) landfilling (L scenario) and incineration with energy recovery (I scenario).

LCC inventory

Data used for the eLCC are mainly primary information gathered by the producer. Materials cost are the acquisition cost provided by the material supplier; since the PP 23 HGM is a new material a cost range, representative of a different acquisition amount (50÷600 ton per year), was given. Compressed air and transport cost have been retrieved from the current activities costs so they could be consider robust data.

Table 61 LCC inventory dashboard case study

Life cycle stage	**Flow**	**Unit cost**	**Source**
Material	PP 65.40 U	1.45 €/kg	Primary data
	PP 23 HGM	3.3 – 3.9 €/kg	Primary data
Production	Electricity	0.12 €/kWh (average European price)	(Eurostat 2016a)
	Compressed air	0.04 €/Nm^3	Primary data
Transports	Transports	1.1 €/km	Primary data
Use	Diesel	1.26 €/litre (average European price)	(Eurostat 2016a)

S-LCA inventory

The data inventory for S-LCA has been developed according to the quantitative approach of the Handbook for Product Social Impact Assessment (cfr. § 7.1.3). In particular data related to the manufacturing plant of Magneti Marelli were collected while it was not possible to involve other life cycle stages and companies. For this reason social data are the same for both solutions since any changes are expected at manufacturing plants level between the two materials.

Data collected at site level (San Benigno plant, Italy) are allocated to the functional unit according to an allocation factor based on the working hours. In particular the equation (30) was used to determine the allocation factor (Table 62).

Table 62 Data for allocation factor of Magneti Marelli plant dedicated to dashboard production

Parameter	**Unit**	**Value**
Dashboard produced in 2015	Numbers	955
Total amount of working hours dedicated to dashboard production	Hours	7,908
Total amount of working hours in 2015	Hours	68,657
Allocation factor	---	0.12

The performance indicator values, allocated to the product, are reported in Table 63. In this case data aggregation was done only considering the single plant, using the same formula described in crf. § 7.1.3.

Table 63 Social data allocated to FU dashboard case study

	Performance Indicators	**Unit**	**Allocated Data**
Workers	Number of hours of health & safety training given during the reporting period.	Hours	1.18
	Average number of incidents during the reporting period.	Number	0.46
	Percentage of workers whose wages meet at least the legal or industry minimum wage and their provision fully complies with all applicable laws.	%	100%
	Percentage of workers who are paid a living wage.	%	100%
	Percentage of workers whose social benefits meet at least legal or industry minimum standards and their provision fully complies with all applicable laws.	%	100%
	Percentage of workers who exceeded 48 hours of work per week regularly during the reporting period.	%	0%
	Number of hours of child labour identified during the reporting period.	Hours	0
	Number of actions during the reporting period targeting business partners to raise awareness of the issue of child labour.	Actions	0

	Performance Indicators	**Unit**	**Allocated Data**
Workers	Number of hours of forced labour identified during the reporting period.	Hours	0
	Number of actions during the reporting period targeting business partners to raise awareness of the issue of forced labour.	Actions	0
	Number of complaints identified during the reporting period related with discrimination.	Complaints	0
	Number of actions taken during the reporting period to increase staff diversity and/or promote equal opportunities.	Actions	0
	Percentage of workers identified during the reporting period who are members of associations able to organise themselves and/or bargain collectively.	%	40.17%
	Percentage of workers who have documented employment conditions.	%	100%
	Number of hours of training per employee during the reporting period.	Hours	1.11
	Percentage of workers with direct family responsibilities who were eligible for maternity protection, or to take maternity, parental, or compassionate leave during the reporting period.	%	1%
	Percentage of workers who participated in a job satisfaction and engagement survey during the reporting period.	%	34%
	Worker turnover rate during the reporting period.	%	8%
Local communities	Number of programs targeting capacity building in the community during the reporting period.	Programmes	0
	Number of people in the community benefitting from capacity building programmes during the reporting period.	Persons	0
	Number of programmes or events targeting community engagement during the reporting period.	Programmes	0
	Number of new jobs created during the reporting period.	New jobs	0
	Number of jobs lost during the reporting period.	Jobs lost	0

7.2.4. Impact assessment

LCIA

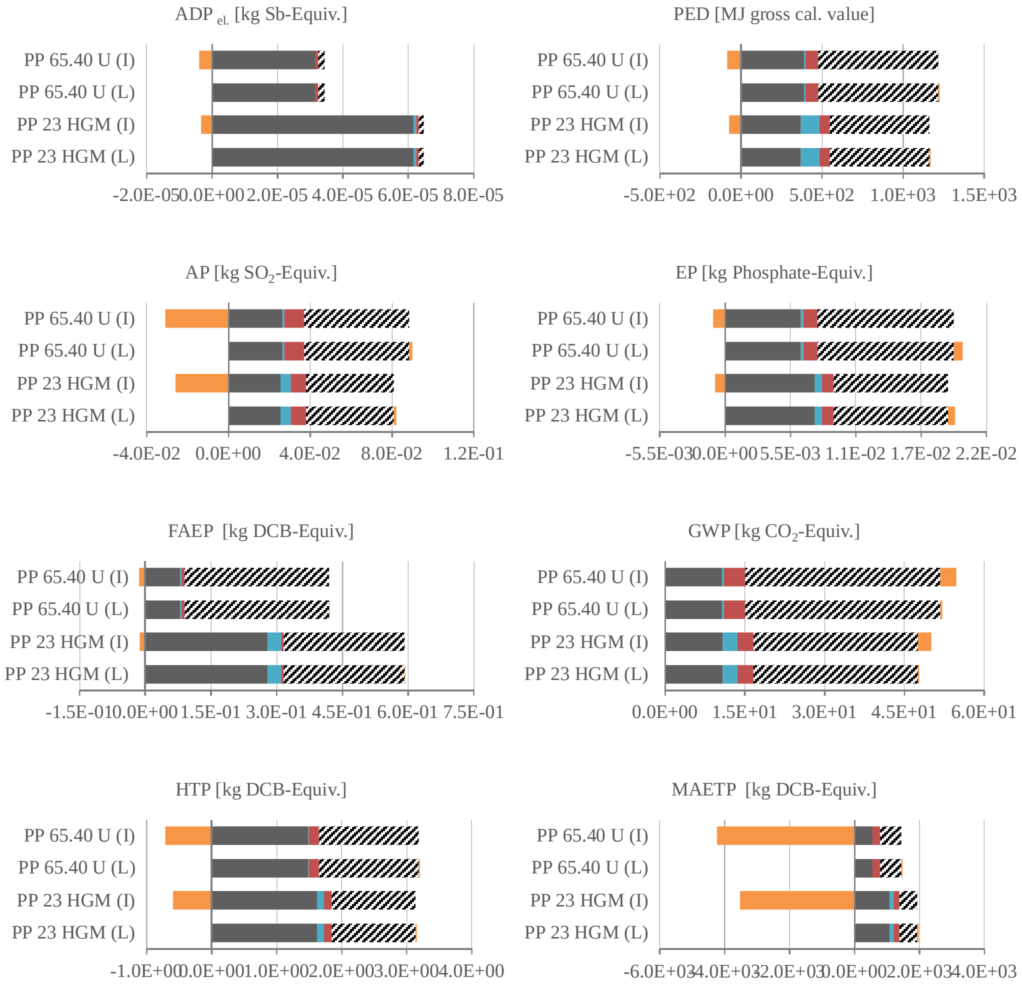
Environmental figures are shown according to the following life cycle stages: raw materials, including their extraction and processing; manufacturing, including energy and scrap flows due to production technologies; transports, including transportation of materials to manufacturing plant and dashboard to assembly plant; End-of-Life, including shredding and disposal of waste. Overall an environmental impact decrease ranging between 2% and 16% was found for the innovative solution (PP 23 HGM) thus suggesting it is the preferable design. On the other side, the different reinforcement material (HGM) is responsible for higher impacts in four environmental impact categories ($ADP_{el.}$, FAEP, MAETP and ODP) (Figure 61, Table 64). This is mainly due to the raw materials involved in the HGM production stage, silica in particular, which is responsible for a potential impact to resource depletion ($ADP_{el.}$) twofold larger than the talc processing. In the fiberglass industry this material is considered critical in terms of availability but very strict specifications generally limit the use of alternatives (van Oers et al. 2002).

Indeed the contribution analysis shows that raw materials and use stage have the major impacts in the overall dashboard life cycle (Figure 61) thus confirming the outcomes from recent studies concerning the same component (Andriankaja et al. 2009; Tharumarajah and Koltun 2010). Moreover, a trade-off between use stage and material production step is found, as generally stressed in the previous analysis about lightweighting (Raugei et al. 2015). In this study, the use stage contribution reduction, associated with an increase of raw material impact, is found particularly in terms of resource depletion (-16% use stage, +90% raw materials) and ecotoxicity effects, while a slight trade-off is seen for the GWP (-16% use stage).

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

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

The EOL stage was found to be negligible when the landfill scenario is assumed, while the energy recovery from the final incineration makes this stage relevant in those categories sensitive to the energy process (Figure 61). Overall, when the incineration scenario is assumed both solutions reach a lower impact in all the categories (due to the avoided burdens from energy recovery), therefore the landfill disposal is to be discouraged in any case with the exception of the GWP. However the different EOL scenarios – landfill or incineration - do not affect the comparison between the two solutions in a considerable way, and the innovative solution is found better than the standard one.



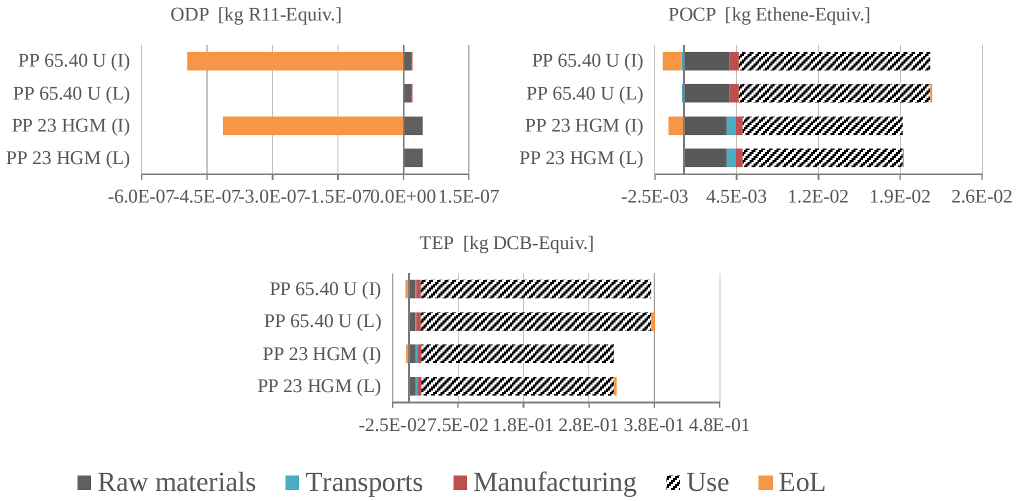


Figure 61 Environmental impact comparison between the standard (PP 65.40 U) and the innovative (PP 23 HGM) solutions (characterization results), for landfill (L) and incineration (I) scenarios

Table 64 Environmental impacts comparison between the standard (PP 65.40 U) and the innovative (PP 23 HGM) solutions (characterization results), for landfill and incineration scenarios

		Landfill scenario			**Incineration scenario**		
Category	**Unit**	**PP 65.40 U**	**PP 23 HGM**	**Variation**	**PP 65.40 U**	**PP 23 HGM**	**Variation**
ADP$_{el.}$	kg Sb$_{-eq}$/FU	3.45E-05	6.48E-05	87.8%	3.06E-05	6.15E-05	101.2%
AP	kg SO$_{2-eq}$/FU	8.99E-02	8.21E-02	-8.6%	5.75E-02	5.50E-02	-4.2%
EP	kg Phosphate-$_{eq}$/FU	2.00E-02	1.94E-02	-3.2%	1.82E-02	1.79E-02	-1.9%
FAEP	kg DCB$_{-eq}$/FU	4.21E-01	5.93E-01	40.7%	4.05E-01	5.79E-01	43.0%
GWP	kg CO$_{2-eq}$/FU	5.21E+01	4.78E+01	-8.2%	5.47E+01	5.00E+01	-8.6%
HTP	kg DCB$_{-eq}$/FU	3.20E+00	3.15E+00	-1.7%	2.47E+00	2.54E+00	2.7%
MAETP	kg DCB$_{-eq}$/FU	1.48E+03	1.96E+03	32.7%	-2.79E+03	-1.61E+03	-42.5%
ODP	kg R11$_{-eq}$/FU	2.07E-08	4.45E-08	115.2%	-4.75E-07	-3.70E-07	-22.2%

		Landfill scenario			**Incineration scenario**		
Category	**Unit**	**PP 65.40 U**	**PP 23 HGM**	**Variation**	**PP 65.40 U**	**PP 23 HGM**	**Variation**
POCP	kg Ethene-$_{eq}$/FU	2.10E-02	1.88E-02	-10.4%	1.93E-02	1.74E-02	-9.9%
TEP	kg DCB-$_{eq}$/FU	3.76E-01	3.18E-01	-15.5%	3.66E-01	3.09E-01	-15.5%
PED	MJ/FU	1.22E+03	1.17E+03	-4.4%	1.13E+03	1.09E+03	-3.5%

LCC – costs aggregation analysis

Economic assessment results are described according to the following cost categories: materials, manufacturing, transports and use. The perspective used in the analysis could mainly give information to the producer wanting to evaluate the development of the innovative solution by comparing the benefit for the consumer and the higher expenditure necessary for its implementation.

The eLCC results in a total cost for the bottom insert (item) of 18€ and 16.6€ for the standard and the innovative solution respectively (Table 65). The cost breakdown, reported in Table 65, shows that material stage and use stage are the most relevant; in the standard solution their contributions correspond to 18% and 79% respectively, whereas they contribute 37% and 60% in the innovative one. An increase in the material cost is a general trend pointed out in other studies (Witik et al. 2011) and it is confirmed also in this specific case study. The trade-off between production stage and use stage expenditures is in favour of the lightweight solution, where the consistent cost saving during use stage (-30%) manage to counterbalance the material cost increase of the hollow glass spheres composite thus leading to a total cost reduction of 8%. A smaller but not negligible role is played by the lower cycle time which leads to 13% manufacturing cost reduction, thus confirming the relevance of this parameter even from an economic life-cycle perspective (Witik et al. 2011). The transport cost does not significantly influence the total cost.

Table 65 Economic assessment results of standard and innovative solutions (*considering the material average cost from those values proposed by material suppliers and referred to the current year)

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

S-LCA – performance aggregation and evaluation

Table 66 S-LCA results: performance values of dashboard case study (*formula handbook)

Performance indicators	**Unit**	**PLC Indicator***	**PV**	**Performance evaluation**
Number of hours of health and safety training per worker given during the reporting period.	Hours	0.136	-0.864	negative performance
Average rate of incidents during the reporting period.	Number	0.053	-0.053	negative performance
Percentage of workers whose wages meet at least legal or industry minimum standards and their provision fully complies with all applicable laws.	%	100%	100%	target or minimum scenario has been reached
Percentage of workers who are paid a living wage.	%	100%	100%	target or minimum scenario has been reached
Percentage of workers whose social benefits meet at least legal or industry minimum standards and their provision fully complies with all applicable laws.	%	100%	100%	target or minimum scenario has been reached
Percentage of workers who exceeded 48 hours of work per week regularly during the reporting period.	%	0%	0%	target or minimum scenario has been reached
Number of hours of child labour identified during the reporting period.	Hours	0	0	target or minimum scenario has been reached
Number of actions during the reporting period targeting business partners to raise awareness of the issue of child labour.	Actions	0	-1	negative performance
Number of hours of forced labour identified during the reporting period.	Hours	0	0	target or minimum scenario has been reached
Number of actions during the reporting period targeting business partners to raise awareness of the issue of forced labour.	Actions	0	-1	negative performance

Performance indicators	**Unit**	**PLC Indicator***	**PV**	**Performance evaluation**
Number of complaints identified during the reporting period related to discrimination.	Complaints	0	0	target or minimum scenario has been reached
Number of actions taken during the reporting period to increase staff diversity and/or promote equal opportunities.	Actions	0	-1	negative performance
Percentage of workers identified during the reporting period who are members of associations able to organise themselves and/or bargain collectively.	%	40.17%	40.17%	positive performance
Percentage of workers who have documented employment conditions.	%	100%	100%	target or minimum scenario has been reached
Numbers of hours of training per employee during the reporting period.	Hours	0.128	-0.872	negative performance
Percentage of workers with direct family responsibilities who were eligible for maternity protection, or to take maternity, parental or compassionate leave during the reporting period.	%	1%	1%	positive performance
Percentage of workers who participated in a job satisfaction and engagement survey during the reporting period.	%	34%	34%	positive performance
Worker turnover rate during the reporting period.	%	8.29%	-8.29%	negative performance
Number of programmes during the reporting period to enhance community health or safety.	Programmes	0	-1	negative performance
Number of adverse impacts on community health or safety identified during the reporting period.	Adverse impacts	0	0	minimum scenario has been reached
Number of programmes during the reporting period to enhance community access to tangible resources or infrastructure.	Programmes	0	-1	negative performance

Performance indicators	**Unit**	**PLC Indicator***	**PV**	**Performance evaluation**
Number of adverse impacts on community access to tangible resources or infrastructure during the reporting period.	Adverse impacts	0	0	target or minimum scenario has been reached
Number of programmes targeting capacity building in the community during the reporting period.	Programmes	0	-1	negative performance
Number of people in the community benefitting from capacity building programmes during the reporting period.	Persons	0	-1	negative performance
Number of programmes or events targeting community engagement during the reporting period.	Programmes	0	-1	negative performance
Number of new jobs created during the reporting period.	New jobs	0	-1	negative performance
Number of jobs lost during the reporting period.	Jobs lost	0	0	target or minimum scenario has been reached

7.2.5. **Results integration and interpretation**

TOPSIS method is applied to integrate LCA, LCC and S-LCA results. The decision matrix is reported in Table 67.

The weights of sustainability indicators, obtained from the intuitionistic fuzzy method, are referred to 32 criteria. Overall those sustainability criteria are measured by means of the LCA, LCC and S-LCA impact categories/performance indicators; this correspondence is provided in Annex C.

Table 67 LCSA results of dashboard case study (decision matrix)

	Indicator	**ID**	**Unit**	PP 65.40 U	PP 23 HGM	Score evaluation
LCC	Raw material cost	LCC$_1$	€/FU	3.2	6.19	Worst
	Production cost	LCC$_2$	€/FU	0.63	0.54	Better
	Use cost	LCC$_3$	€/FU	14.3	9.94	Better
LCA	GWP	LCA$_1$	kg CO$_{2\text{-eq}}$/FU	5.2E+01	4.8E+01	Better
	AP	LCA$_2$	kg SO$_{2\text{-eq}}$/FU	9.0E-02	8.2E-02	Better
	ADP$_{\text{elements}}$	LCA$_3$	kg Sb-eq/FU	3.5E-05	6.5E-05	Worst
	PED	LCA$_4$	MJ/FU	1.2E+03	1.2E+03	-
	HT	LCA$_5$	kg DCB$_{\text{-eq}}$/FU	3.2E+00	3.2E+00	-
	FAEP	LCA$_6$	kg DCB$_{\text{-eq}}$/FU	4.2E-01	5.9E-01	Worst
	ODP	LCA$_9$	kg DCB$_{\text{-eq}}$/FU	2.1E-08	4.5E-08	Worst
	EP	LCA$_{10}$	kg DCB$_{\text{-eq}}$/FU	2.0E-02	1.9E-02	Better
	POCP	LCA$_{11}$	kg R11$_{\text{-eq}}$/FU	2.1E-02	1.9E-02	Better
S-LCA	Health and Safety workers	S-LCA$_1$	h/FU	0.136	0.136	-
		S-LCA$_2$	number/FU	0.053	0.053	-
	Wages	S-LCA$_3$	%	100%	100%	-
		S-LCA$_4$	%	100%	100%	-
	Social benefits	S-LCA$_{13}$	%	100%	100%	-
	Working hours	S-LCA$_{14}$	%	0%	0%	-
	Child labour	S-LCA$_{15}$	h/FU	0	0	-
		S-LCA16	actions/FU	0	0	-
	Forced labour	S-LCA17	h/FU	0	0	-
		S-LCA$_{18}$	actions/FU	0	0	-
	Discrimination	S-LCA$_5$	complaints/FU	0	0	-
		S-LCA$_6$	actions/FU	0	0	-
	Freedom of association	S-LCA$_{19}$	%	40.17%	40.17%	-
	Employment relationship	S-LCA$_{24}$	%	100%	100%	-
	Training and education	S-LCA$_7$	h/FU	0.128	0.128	-

	Indicator	**ID**	**Unit**	PP 65.40 U	PP 23 HGM	Score evaluation
S-LCA	Work-life balance	S-LCA$_{21}$	%	1%	1%	-
	Job satisfaction	S-LCA$_{8}$	%	34%	34%	-
		S-LCA$_{9}$	%	8.29%	8.29%	-
	Health and Safety local community	S-LCA$_{10}$	programmes/FU	0	0	-
		S-LCA11	adverse impacts/FU	0	0	-
	Community engagement	S-LCA$_{12}$	programmes/FU	0	0	-
	Employment local community	S-LCA$_{24}$	new jobs/FU	0	0	-
		S-LCA$_{25}$	jobs lost/FU	0	0	-

Results of TOPSIS analysis are presented in the following graphs; three levels of results are presented: 1) single sustainability score, corresponding to the TOPSIS ranking score; 2) sustainability dimensions contributions; 3) stakeholders' points of view.

When all sustainability indicators are considered, the PP 65.40 U solution is ranked as the best alternative (the higher value is better) (Figure 62). Despite the light solution (PP 23 HGM) gains the best score in the majority of the sustainability indicators (Table 67), the integrated outcomes are in favour of the reference solution. This can be mainly ascribed to two mains elements: the weights associated to the indicators (Annex C) and the magnitude of the difference between the two solutions for each indicators. For instance, the PP 23 HGM provides lower impacts in terms of GWP, PED and EP (within a range of -3% and 8%) which are also indicators with the highest weights among the environmental indicators. In the integrated analysis, those benefits are however covered by the increase in other impact categories (ODP and FAETP) which have lower weights but larger delta (difference between light and ref. solutions), in a range of +40÷90%. Similar consideration can be done concerning economic indicators: in this case the benefit in terms of production stage cost (highest weight among economic criteria) is crossed by the effect of the raw material which doubles the reference material. In fact, outcomes show that, when environmental and economic impacts are presented separately the reference solution was found preferable (Figure 63). Concerning the social dimension, a difference between the two solutions cannot be seen since data are only referred to the manufacturing stage which is not expected to be affected by the different design solution from a social point of view. As a consequence the social dimension does not contribute in the integrated sustainability analysis (Figure 63).

A third level of results regards the stakeholders' points of view. The TOPSIS analysis has been carried out according to decision makers' judgment representative of an aggregated view of academy, industry, automotive and other population groups. Figure 63 shows the sustainability score according to the different perspectives; as it can be seen a general agreement can be observed among the groups. This was expected since such agreement was already identified in the survey results dispersion analysis (cfr. § 6.3.2). However, it can be argued that if different stakeholder groups, representative for alternative, or even opposite interests would be included, than such an agreement could not be guaranteed.

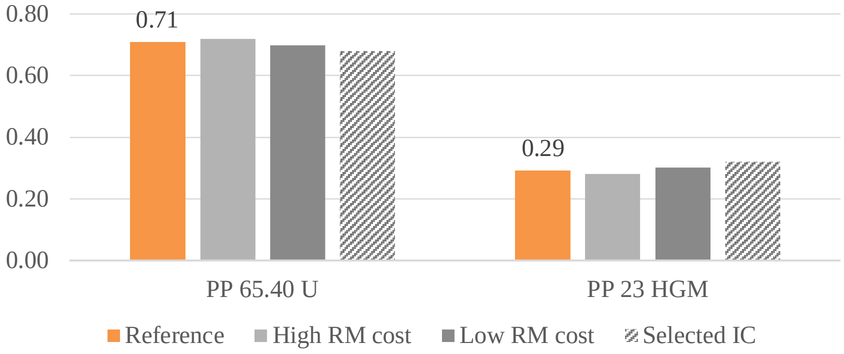


Figure 62 Ranging of alternatives according to TOPSIS method (the higher is better) (Reference: assuming average material cost; High RM cost: assuming the highest raw material cost; Low RM cost: assuming lowest raw material cost; Selected IC: assuming only the relevant environmental impact categories according to stakeholders preference)

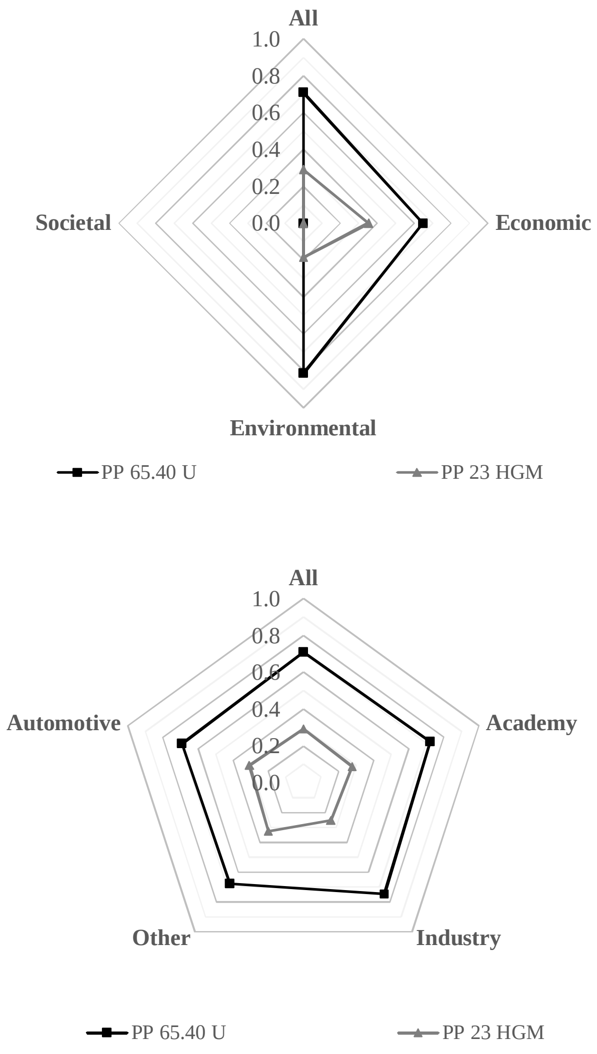
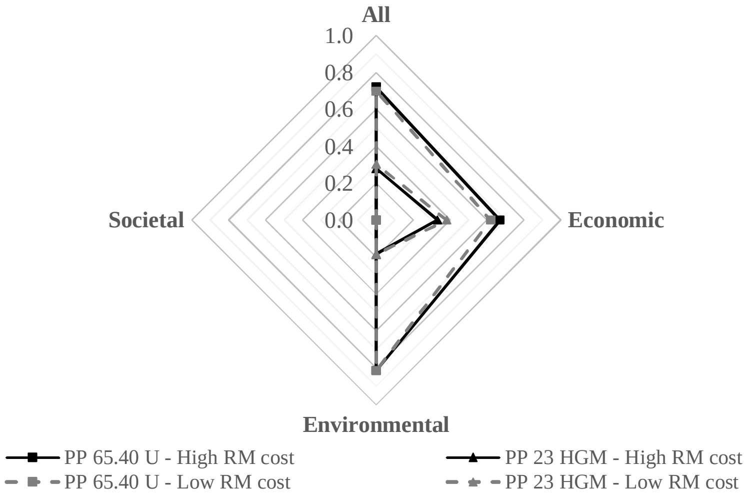


Figure 63 Ranging of alternatives: sustainability dimensions and stakeholders' points of view (the higher is better)

Results are presented also based on three alternative scenarios: the first when the raw material cost of PP 23 HGM is assumed equal to the highest value (provided by the material supplier) (High RM cost), the second where the lowest cost is included (Low RM cost), the third scenario where only three environmental categories are included, in particular GWP, PED and $ADP_{el.}$. Overall the reference solution remains the best option from a sustainability point of view however the distance between PP 65.40 U and PP 23 HGM is reduced between 5% and 15% when the PP 23 HMG cost is reduced and environmental impact categories are selected respectively (Figure 62).



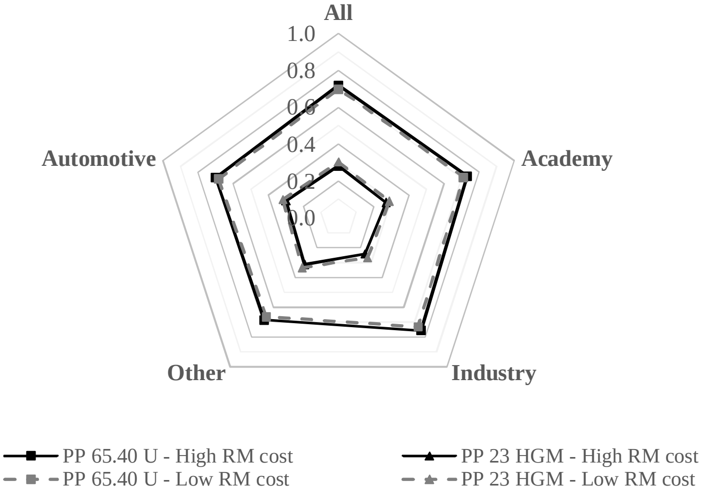


Figure 64 Ranging of alternatives: comparison of alternative scenarios of raw material cost (High RM cost: assuming the highest raw material cost; Low RM cost: assuming lowest raw material cost) (the higher is better)

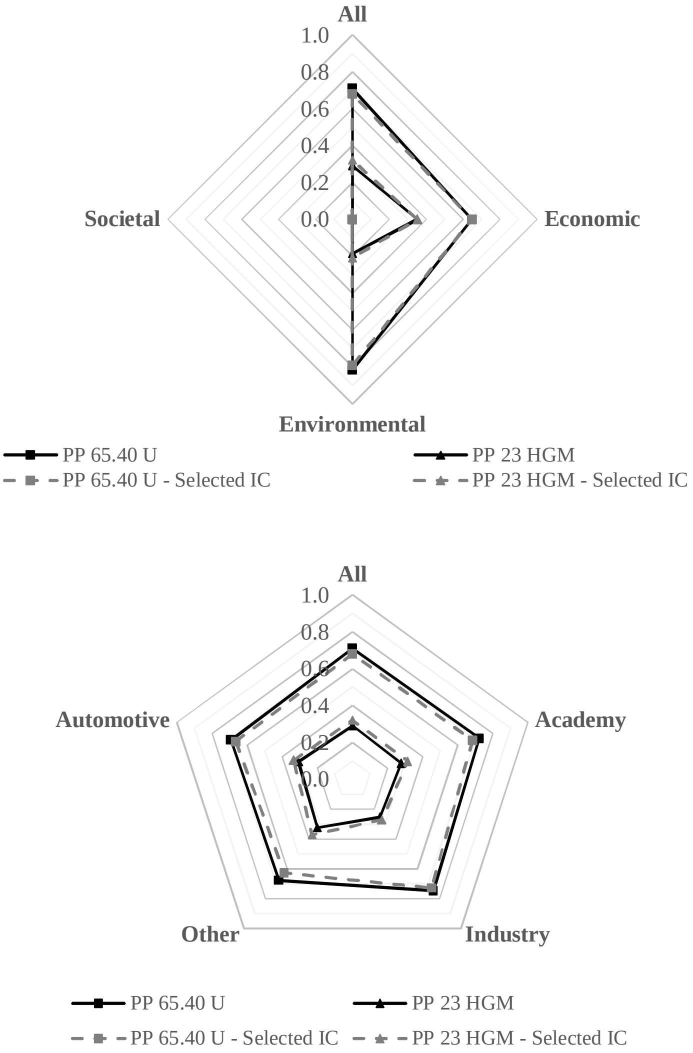


Figure 65 Ranging of alternatives: comparison of alternative scenarios of impact categories (PP 65.40 U and PP 23 HGM: assuming all the assessed environmental impact categories; Selected IC: assuming only the relevant environmental impact categories) (the higher is better)

8. Conclusions and final remarks

The activity presented in this thesis deals with the Life Cycle Sustainability Assessment application in the automotive sector with the aim of proving contribution both in terms of methodology progress and evaluation of applicability and challenges to propose this methodology as a supporting tool in the lightweight design of vehicle components.

Whereas environmental sustainability metrics and related automotive manufacturers' awareness have been increasing, social sustainability at product level is still at an early stage. Nevertheless, the automotive sector is particularly sensitive to programmes for evaluating sustainability of its products, as demonstrated by the number of initiatives in which companies are involved (i.e. "Self-Assessment Questionnaire on CSR/Sustainability for Automotive Sector Suppliers", Roundtable for Product Social Metrics initiative).

After a literature review regarding tools and methodologies currently used by carmakers to evaluate sustainability of their products/activities, it was found that most of the expertise regards LCA application for the environmental assessment at product level and company-level sustainability compliance programmes complying with international and industry standards (i.e. corporate level standards as GRI). Nonetheless the review process only refer to those practices publically available which do not necessary correspond to internal procedures of OEMs. Indeed, innovation and sustainability represent competition elements and then activities upon those topics could be confidential. As a consequence discussions and conclusions could be representative for published sources and activities directly developed in this research.

Overall, there is clear consensus on the need of addressing sustainability issues, based on the "three pillar" concept, also at product level and so developing and testing robust and practicable methodology for measuring and managing social impacts which could be integrated with environmental and economic analysis already present. In response to this, the LCSA, a combination of LCA (environment), LCC (economy) and S-LCA (society), has been selected among other framework.

In this research the LCSA practicability has been addressed: the focus was turned to the S-LCA methodology aspects and a mathematical method to integrate LCA, LCC and S-LCA results. However, also environmental and economic issues stemmed from real case studies of lightweight solutions have been evaluated to provide insights to be conveyed in the Life Cycle Sustainability Assessment framework.

One of the principle behind this research is to contribute to the methodological developments by adopting a sector-specific and context-specific approaches as opportunity to enhance the practicability of the method among organizations and strengthen its role as a decision-supporting and strategic tool.

This research represents one of the first work dealing with the sustainability assessment of products by means of the Life Cycle Sustainability Assessment in the automotive sector. All the conclusion and final remarks are drawn by considering the specific field and context where the LCSA has been applied: the early design phase of automotive components during which the designer has to make decisions in terms of materials, geometry, technologies, suppliers, etc. and, indeed, inevitably has to take into consideration sustainability aspects which can be encountered even far in the product life cycle. First, conclusions for each life cycle-based methodologies are drawn according to the presented research questions, then limitations and future research are presented.

8.1. LCA: potentialities and critical issues of lightweighting

- The current available databases, in particular GaBi, were reviewed to identify available dataset concerning materials production (polymers, fibres, metals), technologies dedicated to metals and composites manufacturing, and processes for the EOL treatment of vehicles/components and materials recycling. Due to its limited coverage about some specific materials and processes, the desk research and data gathering in collaboration with OEMs allowed collecting a number of data (i.e. energy consumption, scraps production) regarding: composite (e.g. carbon and glass fibres reinforced PA410, unidirectional tape and woven tape reinforcement, PP reinforced with 23% Hollow Glass Microspheres, PP filled with of wood fibres), manufacturing technologies (e.g. Advanced Sheet Compression Moulding, pre-preg. process, Resin Transfer Moulding), EOL processes (e.g. shredding, metal separation). It is important to stress that LCA case studies included in this research mainly applied composite or aluminium as light materials, therefore data availability review referred to these materials classes and do not cover others like new metal alloys (i.e. steel-advanced alloy).
- It was observed that a delicate trade-off exists between benefit in the use stage and impact increase in the production stage; this is particularly evident when the lightweight design is applied in the EVs. Results from the case studies supported the idea that vehicle propulsion system and material pairs are the design elements mostly influencing the final results. The relationship is evaluated by means of the additional index (break-even point,$\Delta_{I/M}^{P}$). In fact, especially for GWP and PED, the ICE case studies gain positive delta impact values, and generally higher that the ones of EVs. These findings suggest that a better performance can be achieved when the lightweight solution is applied for ICE vehicles. This finding is confirmed also by the breakeven analysis; whereas the lightweight solutions for EV provide break-even points generally higher than the assumed vehicle life span (150,000 km), the majority of lightweight applications to ICE vehicle shown a break-even point equal to zero. The material pairs was found to be another significant elements, in fact when lightweighting involves materials from the same class (Steel-to-Al and Composite-to-Composite) the new solution is always better than the reference one. On the contrary, when the design changes from a metal-based solution (typically steel-based) to a hybrid solution, the achieved benefit are more uncertain.
- The weight reduction leads to improvements in terms of fuel consumption and gives benefits for those impact categories where the use stage is more involved (i.e. GWP, PED), whereas indicators mostly affected by the material stage were found to become worse (resource depletion). LCA outcomes confirmed that a slight balance between use

stage benefit and raw material stage was found concerning the GWP but it reveals more consistent regarding other environmental indicators. This demonstrates the importance of enlarging the environmental assessment to a diverse set of impact categories, in addition to the CO_2 emissions typically addressed in the sector, to detect the effective advantages of a lightweight solution. In particular the resource depletion was found a challenging issue and this point could have significant implications for future policy planning regarding the automotive sector. As far as EOL stage is concerned, this study showed that evaluating this stage according to the LCA impact categories could not provide all the necessary information during an early design phase; in particular the designer needs to take into account the specific ELVs target in terms of recyclability/recoverability index calculated according to the ISO 22628.

- The relevance of certain environmental issues was evaluated; the review and the results from the online survey, with respect to the automotive group, demonstrated that Greenhouse Gasses effects, resource depletion and energy demand are generally perceived as the most significant for the sector. However, further considerations should necessary take into account the robustness of the available indicators like $ADP_{el.}$.

8.2. LCC: lessons learned from review and case study

- Literature review of LCC in the automotive sector showed that the evaluation of economic feasibility of lightweight solutions struggles with the complexity of the product (number of materials, processes and actors involved) and the lack of specific standard. The revised studies generally did not rely on the principles of the Code of practice so LCC type, perspective and other elements were seldom defined.
- In response to this, discussion about some methodology settings were provided. First, the environmental LCC type was selected as the most appropriate to make LCC consistent for a LCSA study. The perspective was defined in a more extensively way. Since the decision of implementing a lightweight solution or not does make sense only if the production cost is compared with the benefits that this solution will produce in the use stage (in favour of the consumer), then a ‘hybrid perspective’ was proposed. It would represent a ‘user perspective’ where the production cost is assumed in place of the acquisition cost. In such a way the producer can evaluate the benefit for the consumer, achieved by its higher expenditure and thus decide the proper price for the innovative solution. It was found that very few reasoning are present concerning externalities and in this research only the cost for CO_2 emissions was analysed. Finally, some efforts were dedicated to clearly describe all the cost categories, formulas and data behind them, in particular those costs involved in the manufacturing stage.
- It was found that many data could be necessary to evaluate the economic feasibility of a lightweight solution, moreover the cost modelling has been generally hindered by confidentiality that applies to any specific cost data. As a consequence data availability remains an issue but if the analysis is developed internally by the company this problem is expected to be overcome. In this research, a clear list of cost categories, in particular information regarding manufacturing processes, was developed, also in collaboration with an automotive manufacture, and was validated by a real case study with the aim of testing if this information could be effectively collected during the design phase.

- It was observed that steel replacement with carbon fibers composite is responsible for an increase of the product cost which is not balanced by the fuel cost reduction. The high material cost and the high cycle time production are the main causes. Indeed, the use of composites in the automotive sector is still too low to guarantee an optimization of processes and competitive cost if compared with traditional materials. Only when an optimistic future scenario was assumed (-50% material cost and -60% cycle time reduction) then the lightweight solution was found economically beneficial. In this case outcomes stressed that the propulsion system does not influence the final results, thus manufacturing process optimization and composite cost were found the most important elements to be improved. As for the GWP, the break-even analysis was developed as a way to determine the economic convenience of a solution along its whole life cycle; moreover such analysis represents a simple way to integrate environmental (GWP) and economic results. In fact, by comparing the break-even point values it is possible to determine if the lightweight solution is preferable from an environmental or economic point of view (the lower value the better). Indeed, it was found that break-even point could be affected by the fuel cost discounting. The contribution of CO_2 emissions cost was analysed by assuming the Emission Trading System values; only when the average cost reached in mid-2008 is assumed such externality was found relevant, otherwise this figure was found insignificant if compared with others.

8.3. S-LCA: a conceptual map for guiding the goal and scope and inventory phases

- Most of the scientific articles published so far have addressed the applicability of S-LCA by focusing on the selection of suitable and relevant indicators, and on data collection, relying upon the existing guidelines and without questioning key aspects that make the analysis challenging, such as functional unit, system boundary definition and the scope of the assessment (company vs. product), just to mention some. Thus, a critical review was undertaken on how the key elements affecting the inventory phase of S-LCA applications were dealt with (i.e. functional unit, system boundaries, perspective), with the ultimate purpose of identifying and developing a structured approach to S-LCA.
- A conceptual map was elaborated in which all the elements pointed out by the review were grouped into seven nodes. Each node represents a crucial point where a decision needs to be taken in order to carry out the analysis. Specific questions that may aid practitioner to clarify the meaning of each node and to go ahead in a more aware assessment were shown, where relevant. The nodes are then placed into four steps representing a suggestion for an orderly procedure of analysis. The aim of the conceptual map is not to solve open methodological issues but to push practitioners in critically facing all of them and therefore contribute to the enhancement of the research in the S-LCA field.
- The conceptual map was then analysed with respect to the automotive sector, with the ultimate goal of contributing to the development of the S-LCA methodology tailored to the peculiarities and needs of the sector. Overall the automotive industry was found to have a high maturity in the life cycle-based sustainability assessment, however the few number of S-LCA applications did not allow to answer all the conceptual map nodes thus pointing out the next challenges and directions which need to be faced. In fact, the analysis of the sector and its contribution to further tailoring the conceptual map to it

highlighted that, when both complex products and value chains are involved, such as in the automotive sector or in the electronic and electrical equipment, just to mention some, both the information on social performances at product and company level are relevant. The latter provides a measure of the degree to which a company is able to manage the social aspects of concern along the value chain, independently from the product/service delivered, and according to its level of influence. This information is relevant also in light of the Directive 2014/95/EU on disclosure of non-financial and diversity information by certain large companies and groups: the companies concerned will be called to disclose information on policies, risks and outcomes as regards environmental matters, social and employee-related aspects, respect for human rights, anti-corruption and bribery issues. S-LCA can already support this requirement, as present applications adopt a company-driven approach: also when a specific product is the object of the analysis, the reporting of the results in relation to the functional unit seems an artifice, as indeed they do not bring a product-specific information but simply the information is allocated to the product. Regarding the social information at product level, this is considered relevant too for two main purposes: to build the profile of products also in relation to the social aspects, besides the technical, quality-related and environmental ones; to be able to better conceive and design products and services taking into account also the social variable.

- The indicators selection is a challenging issue which arose from the literature. The relevance is often mentioned as the criterion for indicators selection but further insights on how it is evaluated are generally not provided. Most of the revised studies rely on the indicators proposed in the UNEP/SETAC methodological sheets, a few stressed the need of introducing additional indicators specific for their case studies. In this research, the social indicators proposed by the UNEP/SETAC methodological sheets were analysed together with those proposed by the Roundtable for Product Social Metrics initiative and the ones proposed by the PSILCA database (version 1). The list from the quantitative approach of the Roundtable for Product Social Metrics initiative was selected as the starting point for testing the main challenges in terms of data gathering and data allocation.

8.4. LCSA: integrating results by means of MCDA method and online survey for criteria prioritization

- The Multi-Criteria Decision Analysis (MCDA) was identified as a suitable approach to integrate LCA, LCC and S-LCA results. In fact, MCDA helps decision makers to choose the best option when a wide range of criteria has to be considered. After a review of the most used and suited MCDA methods, the TOPSIS, combined with fuzzy set approach, was selected. This method develops ranking of alternatives assuming that the most preferred alternative should have the shortest distance from the positive ideal solution as well as the farthest distance from the negative ideal solution. Overall, a set of quantified social, economic and environmental sustainability indicators have been identified for the S-LCA, LCC and LCA respectively, and an online survey was proposed to prioritize them according to the experts' judgments belonging to different sectors. The survey was mainly addressed to people belonging to the automotive sector, both as members of industry and as researchers in the sustainable transportation field, and people working in the sustainability and Life Cycle Assessment area. Next, results from the survey were analysed and furthermore treated by means of the intuitionistic fuzzy set method in order to avoid ambiguity and determine the weights of indicators.

8.5. LCSA case studies: implementing the Roundtable for Product Social Metrics and applying the TOPSIS method

- The goal and scope was defined according to the proposed conceptual map and its nodes were discussed with reference to the peculiarities of the sector (i.e. perspective definition, double-layer approach for the system boundaries definition) trying to identify sector-specific rules from the social point of view, as a step forward towards consistent results to make it fully tailored to the automotive sector.
- The data inventory was developed according to the quantitative approach of the Roundtable for Product Social Metrics initiative which uses only numerical data measured as performance indicators, grouped into several social topics. The case studies gave the opportunity to collect primary data al site level; furthermore companies were involved in a process of critical discussion of indicators in terms of relevance/appropriateness, affordability/availability, understanding and completeness.
- The S-LCA impact assessment method proposed by the Roundtable for Product Social Metrics initiative was applied. It is a Type I method whose main steps are data allocation and data referencing when Product Life Cycle (PLC) indicators (aggregated value of the indicator along the life cycle) are compared to reference values in order to evaluate the relative positive or negative performance of the product in a given social topic. This research represents one of the first example of application of this method, therefore strong points and weaknesses were critically discussed.
- The TOPSIS applicability was proved and both advantages and limits could be identified. As other methods from literature, its use is strictly linked to comparative analysis therefore other approaches need to be used in the case of absolute analysis as in the case of the knuckle study. Overall, the TOPSIS method allowed to define the best alternative also when a high number of indicators are used since the mathematical operations and data could be easily handled in an Excel programmed workbooks. Moreover it could provide results at different levels - single sustainability score, sustainability area and stakeholder group perspective - thus permitting to identify potential trade-off. Nevertheless, the high number of indicators used could hinder the final interpretation in terms of impacts and possible technical solutions. In this sense, limiting the number of indicators could improve the effective use of the method during an early design phase when decisions need to be taken. Also the survey was found a practicable way to identify the priority level of a set of sustainability criteria and its use in combination with the MCDA was found an effective way to enhance stakeholder involvement in the sustainable design context.

8.6. Limitations of the study and future research

There are a lot of opportunities for future works. First, one of the limitations of this research is the set of social indicators which was used and which could be improved in terms of completeness, understanding and feasibility. Moreover the research was focused on collection of site specific data, so all the life cycle stage where such information could not be gathered (e.g. raw materials, EOL) were excluded from the assessment. One option could be improving the inventory by using the PSILCA database whose indicators are inspired by the UNEP/SETAC methodological sheets, however this could be done in accordance with the future database progress. Enlarging the list of sustainability criteria to indicators out of the (environmental) LCA context could enhance results utilization by the designer. An example is the analysis of End of Life, when including elements from the ISO 22682 and ELVs targets besides the LCA was found fundamental. Nevertheless, the generic indications of the ISO 22628 could lead to a lack of sensitiveness for two main reasons: the recyclability/recoverability assessments using ISO 22628 do not take into account the loss/efficiency of the recycling/recovery of materials; a clear and systematic way to approach evaluations on the potential disassembly of a component is still missing. So in the dilemma of achieving the lightweight and the vehicle recyclability target, further research could regard methods for better calculating the direct correlation between a given design solution of a component and the recyclability of the whole vehicle.

Secondly, it is important to stress that a limit to this research is represented by the different nature of results which are integrated by means of the TOPSIS method; in fact, whereas LCA results are impacts, LCC and S-LCA results are performances, so further discussion would concern how this could affect the interpretation of results.

Third, in this research the online survey has only involved certain experts’ groups, however, as different stakeholders are generally involved during a vehicle life cycle, the analysis would be increased by engaging other stakeholder groups whose opinion could be even contradicting.

Considering the specific context of the automotive sector, another direction for the future research would regard the social impacts of vehicle use stage; the relevance of this stage from environmental and economic perspectives, and the concern caused by the trade-off between production and use stage suggest that its evaluation, also at component level, could represent an interesting field of work.

Finally, in order to consider both dimensions (product and organization) in S-LCA, it is proposed to re-define the approach and framework according to the organizational perspective, as laid down in the recent Organization Environmental Footprint and Organizational LCA, which accounts for both organization activities and product portfolio. This implies that social aspects would be evaluated both in relation to the organization behaviour and to the basket of products, thus reconciling the need to keep together the conduct-of-a-company perspective, typical of social evaluations, and the product-oriented approach, inherent to the life cycle and in particular to the functional unit concept.

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Annex A: Use stage modelling

The inventory data for the use stage of the component is calculated by mathematical models that correlates the fuel/energy consumption of the whole vehicle to the fuel/energy use due to the component.

The use stage modelling of the Internal Combustion Engine (ICE) vehicle adopts the analytical car consumption model, based on fuel reduction value (Koffler and Rohde-Brandenburger 2009). The consumption model is based on the following analytical expression:

$$Fuel_{component} = FRV \times \frac{mass_{component}}{100} \times \frac{use_{km}}{100}$$

where:

- Fuel $_{component}$ is the fuel consumption attributed to the component [litres];
- FRV = fuel reduction value, based on the New European Driving Cycle (NEDC), is assumed 0.12 and 0.15 for the diesel and gasoline vehicle respectively (Koffler and Rohde-Brandenburger 2009) [litres/100kg•100km];
- Mass $_{component}$ is the mass of the component [kg];
- Use $_{km}$ is the life-distance [km];

For a comparative purpose, the use stage emissions included in the analysis are CO_2 and SO_2 since they are the only depending on fuel consumption in a proportional way. The emissions values attributed to the component are calculated according to the following equation, which correlates the vehicle emissions to the ones attributable to the component by means of the fuel component (Delogu et al. 2016):

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

where:

- Fuel $_{component}$ is the fuel consumption attributed to the component [litres];
- Fuel $_{vehicle}$ is the fuel consumption of the vehicle [litres/100 km];
- Emissions $_{vehicle}$ are the emission of the vehicle [kg/km].

The technical data of the vehicle depend on the model and they are specified case by case in the chapters.

The use stage modelling of the Electric Vehicle uses a mass-induced energy consumption, over the World-wide harmonized Light duty Test Cycle (WLTC), around 0.69 kWh/100kg·100km (ALIVE - SEAM 2012). Therefore, the energy consumption attributed to the component was calculated through the following formula.

$$energy_{component} = \frac{\left(energy_{MI} \cdot \frac{mass_{component}}{100} \cdot \frac{use_{km}}{100}\right)}{eff_{battery} \cdot eff_{charger}}$$

where:

- energy $_{MI}$ is the mass-induced energy consumption [kWh/100kg·100km];
- mass $_{component}$ is the mass of the component [kg];
- use $_{km}$ is the life-distance [km];
- eff $_{battery}$ is the battery efficiency assumed 85% (ALIVE - SEAM 2012);
- eff $_{charger}$ is the charger efficiency assumed 95% (ALIVE - SEAM 2012).

In the use stage modelling the downsizing effect is assumed negligible and the energy consumption for heating/AC system is excluded as can be considered constant. The European average electricity mix (2014) has been assumed from GaBi database.

Annex B: LCA results

AIR INTAKE			
Impact categories	**Unit**	**Ref.**	**Light**
ADP$_{el.}$	kgSb$_{-eq}$	1.04E-04	1.00E-04
EP	kgPhosphate$_{-eq}$	5.52E-03	3.32E-03
GWP	kgCO$_{2-eq}$	2.58E+01	1.54E+01
ODP	kgR11$_{-eq}$	1.73E-09	3.23E-01
POCP	kgEthene$_{-eq}$	4.42E+02	2.80E+02
PED	MJ	1.10E-02	5.54E-03

THROTTLE BODY			
Impact categories	**Unit**	**Ref.**	**Light**
ADP$_{el.}$	kgSb$_{-eq}$	5.35E-05	6.45E-05
EP	kgPhosphate$_{-eq}$	1.23E-03	1.65E-03
GWP	kgCO$_{2-eq}$	5.71E+00	6.40E+00
ODP	kgR11$_{-eq}$	2.52E-08	4.91E-08
POCP	kgEthene$_{-eq}$	1.24E-03	1.41E-03
PED	MJ	9.82E+01	1.13E+02

FRONT MODULE					
Impact categories	**Unit**	**Ref.**	**Light**	**Ref.**	**Light**
		EOL Current		**EOL Future**	
ADP$_{el.}$	kgSb$_{-eq}$	3.61E-05	9.22E-05	3.03E-05	6.51E-05
EP	kgPhosphate$_{-eq}$	6.75E-02	1.45E-01	6.42E-02	1.26E-01
GWP	kgCO$_{2-eq}$	2.96E+02	3.27E+02	2.83E+02	2.54E+02
ODP	kgR11$_{-eq}$	1.23E-06	2.66E-07	1.23E-06	2.61E-07
POCP	kgEthene$_{-eq}$	1.00E-01	8.72E-02	9.70E-02	7.47E-02
PED	MJ	6.08E+03	6.94E+03	5.55E+03	5.89E+03

CROSS DASHBOARD BEAM					
Impact categories	**Unit**	**Ref.**	**Light**	**Ref.**	**Light**
		EOL Current		**EOL Future**	
ADP$_{el.}$	kgSb$_{-eq}$	1.26E-05	7.53E-05	1.26E-05	6.76E-05
EP	kgPhosphate$_{-eq}$	1.91E-02	2.48E-02	1.91E-02	1.95E-02
GWP	kgCO$_{2\text{-eq}}$	7.21E+01	5.87E+01	7.21E+01	3.65E+01
ODP	kgR11$_{-eq}$	5.49E-08	1.95E-08	5.49E-08	1.54E-08
POCP	kgEthene$_{-eq}$	1.94E-02	1.44E-02	1.94E-02	1.00E-02
PED	MJ	1.65E+03	1.26E+03	1.65E+03	8.92E+02

PEDAL BOX SUPPORT			
Impact categories	**Unit**	**Ref.**	**Light**
ADP$_{el.}$	kgSb$_{-eq}$	4.94E-03	1.84E-03
EP	kgPhosphate$_{-eq}$	2.26E-03	1.44E-03
GWP	kgCO$_{2\text{-eq}}$	7.44E+00	5.82E+00
ODP	kgR11$_{-eq}$	5.16E-08	1.74E-08
POCP	kgEthene$_{-eq}$	1.60E-03	1.41E-03
PED	MJ	1.50E+02	1.25E+02

CROSS MEMBER (Solution 1)			
Impact categories	**Unit**	**Ref.**	**Light**
ADP$_{el.}$	kgSb$_{-eq}$	7.65E-03	7.38E-05
EP	kgPhosphate$_{-eq}$	1.39E-01	5.28E-02
GWP	kgCO$_{2\text{-eq}}$	6.02E+02	2.28E+02
ODP	kgR11$_{-eq}$	6.55E-06	4.30E-08
POCP	kgEthene$_{-eq}$	1.56E-01	5.86E-02
PED	MJ	1.21E+04	4.35E+03

CROSS MEMBER (Solution 2)			
Impact categories	**Unit**	**Ref.**	**Light**
ADP$_{el.}$	kgSb$_{-eq}$	7.65E-03	7.73E-05
EP	kgPhosphate$_{-eq}$	1.39E-01	4.94E-02
GWP	kgCO$_{2\text{-eq}}$	6.02E+02	1.85E+02
ODP	kgR11$_{-eq}$	6.55E-06	1.62E-08
POCP	kgEthene$_{-eq}$	1.56E-01	4.45E-02
PED	MJ	1.21E+04	4.00E+03

SUSPENSION ARM (Solution 1)					
Impact categories	**Unit**	**Ref.**	**Light**	**Ref.**	**Light**
		EOL Current		**EOL Future**	
ADP$_{el.}$	kgSb$_{-eq}$	3.37E-05	1.50E-05	3.37E-05	1.25E-05
EP	kgPhosphate$_{-eq}$	1.61E-02	9.99E-03	1.61E-02	8.19E-03
GWP	kgCO$_{2-eq}$	3.08E+01	3.11E+01	3.08E+01	2.34E+01
ODP	kgR11$_{-eq}$	3.98E-07	5.93E-09	3.98E-07	4.74E-09
POCP	kgEthene$_{-eq}$	1.04E-02	8.21E-03	1.04E-02	6.75E-03
PED	MJ	6.98E+02	6.23E+02	6.98E+02	4.98E+02

SUSPENSION ARM (Solution 2)					
Impact categories	**Unit**	**Ref.**	**Light**	**Ref.**	**Light**
		EOL Current		**EOL Future**	
ADP$_{el.}$	kgSb$_{-eq}$	3.37E-05	1.21E-05	3.37E-05	8.97E-06
EP	kgPhosphate$_{-eq}$	1.61E-02	9.22E-03	1.61E-02	6.85E-03
GWP	kgCO$_{2-eq}$	3.08E+01	3.16E+01	3.08E+01	2.13E+01
ODP	kgR11$_{-eq}$	3.98E-07	9.59E-08	3.98E-07	9.53E-08
POCP	kgEthene$_{-eq}$	1.04E-02	8.20E-03	1.04E-02	6.45E-03
PED	MJ	6.98E+02	6.37E+02	6.98E+02	4.78E+02

FRONT HOOD					
Impact categories	**Unit**	**Ref.**	**Light**	**Ref.**	**Light**
		EOL Current		**EOL Future**	
ADP$_{el.}$	kgSb$_{-eq}$	1.38E-05	4.15E-05	1.38E-05	3.47E-05
EP	kgPhosphate$_{-eq}$	2.39E-02	2.85E-02	2.39E-02	2.38E-02
GWP	kgCO$_{2-eq}$	8.41E+01	8.60E+01	8.41E+01	6.60E+01
ODP	kgR11$_{-eq}$	5.41E-08	4.51E-09	5.41E-08	1.25E-09
POCP	kgEthene$_{-eq}$	2.81E-02	2.42E-02	2.81E-02	2.04E-02
PED	MJ	1.78E+03	1.74E+03	1.78E+03	1.41E+03

FRONT DOOR					
Impact categories	**Unit**	**Ref.**	**Light**	**Ref.**	**Light**
		EOL Current		**EOL Future**	
ADP$_{el.}$	kgSb$_{-eq}$	3.67E-05	1.35E-04	2.73E-05	1.22E-04
EP	kgPhosphate$_{-eq}$	3.22E-02	7.21E-02	2.69E-02	6.13E-02
GWP	kgCO$_{2-eq}$	1.11E+02	1.38E+02	8.99E+01	9.05E+01
ODP	kgR11$_{-eq}$	5.36E-08	-3.67E-08	4.36E-08	-3.74E-08
POCP	kgEthene$_{-eq}$	1.84E-02	3.25E-02	1.29E-02	2.50E-02
PED	MJ	2.33E+03	2.94E+03	1.92E+03	2.23E+03

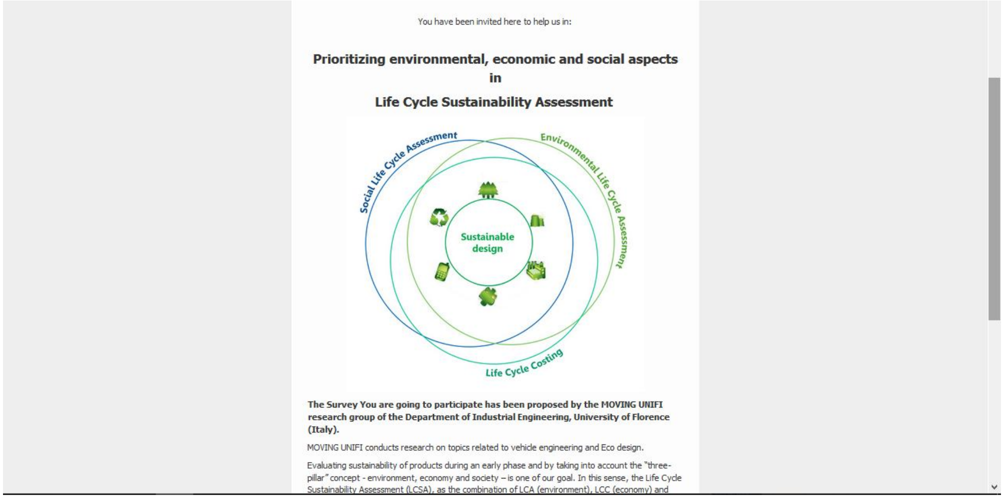
Annex C: List of economic, environmental and social sustainability criteria and online survey screenshot

Sustainability dimension	ID	Criteria	Weight	Method	ID	Indicator	Unit
Economic	C1	Raw material cost	0.038	LCC	LCC1	Raw material cost	€/FU
	C2	Production cost	0.047		LCC2	Production cost	€/FU
	C3	Use cost	0.029		LCC3	Use cost	€/FU
	C4	EOL cost	0.019		LCC4	EOL	€/FU
Environmental	C5	GWP	0.047	LCA	LCA1	GWP	kg CO2-eq/FU
	C6	AP	0.024		LCA2	AP	kg SO2-eq/FU
	C7	$ADP_{el.}$	0.028		LCA3	$ADP_{el.}$	kg Sb-eq/FU
	C8	PED	0.031		LCA4	PED	MJ/FU
	C9	HT	0.029		LCA5	HTP	kg DCB-eq/FU
	C10	EcoT	0.025		LCA6	FAETP	kg DCB-eq/FU
					LCA7	MAETP	kg DCB-eq/FU
					LCA8	TETP	kg DCB-eq/FU

Sustainability dimension	ID	Criteria	Weight	Method	ID	Indicator	Unit
Environmental	C11	ODP	0.024		LCA9	ODP	kg R11-eq/FU
	C12	EP	0.031		LCA10	EP	kg Phosphate-eq/FU
	C13	POCP	0.024		LCA11	POCP	kg Ethene-eq/FU
	C14	Water	0.031		LCA12	Water	m3-eq/FU
	C15	Land use	0.025		LCA13	Land use	kg soil organic carbon/FU
	C16	PM	0.029		LCA14	PM	kgPM2.5-eq/FU
Social	C17	Health and Safety workers	0.040	S-LCA	S-LCA1	Number of hours of health and safety training per worker given during the reporting period.	hours/FU
					S-LCA2	Average rate of incidents during the reporting period.	number/FU
	C18	Wages	0.036		S-LCA3	Percentage of workers whose wages meet at least legal or industry minimum standards and their provision fully complies with all applicable laws.	%
					S-LCA4	Percentage of workers who are paid a living wage.	%
	C19	Discrimination	0.031		S-LCA5	Number of complaints identified during the reporting period related to discrimination.	complaints/FU
					S-LCA6	Number of actions taken during the reporting period to increase staff diversity and/or promote equal opportunities.	actions/FU
	C20	Training and education	0.031		S-LCA7	Numbers of hours of training per employee during the reporting period.	hours/FU
	C21	Job satisfaction	0.031		S-LCA8	Percentage of workers who participated in a job satisfaction and engagement survey during the reporting period.	%
					S-LCA9	Worker turnover rate during the reporting period.	%
	C22	Health and Safety local community	0.031		S-LCA10	Number of programmes during the reporting period to enhance community health or safety.	programmes/FU
					S-LCA11	Number of adverse impacts on community health or safety identified during the reporting period.	adverse impacts/FU

Sustainability dimension	**ID**	**Criteria**	**Weight**	**Method**	**ID**	**Indicator**	**Unit**
	C23	Community engagement	0.029		S-LCA12	Number of programmes or events targeting community engagement during the reporting period.	programmes/FU
	C24	Social benefits	0.036		S-LCA13	Percentage of workers whose social benefits meet at least legal or industry minimum standards and their provision fully complies with all applicable laws.	%
	C25	Working hours	0.036		S-LCA14	Percentage of workers who exceeded 48 hours of work per week regularly during the reporting period.	%
	C26	Child labour	0.036		S-LCA15	Number of hours of child labour identified during the reporting period.	hours/FU
					S-LCA16	Number of actions during the reporting period targeting business partners to raise awareness of the issue of child labour.	actions/FU
	C27	Forced labour	0.036		S-LCA17	Number of hours of forced labour identified during the reporting period.	hours/FU
					S-LCA18	Number of actions during the reporting period targeting business partners to raise awareness of the issue of forced labour.	actions/FU
	C28	Freedom of association	0.031		S-LCA19	Percentage of workers identified during the reporting period who are members of associations able to organise themselves and/or bargain collectively.	%
	C29	Employment relationship	0.031		S-LCA20	Percentage of workers who have documented employment conditions.	%
	C30	Work-life balance	0.029		S-LCA21	Percentage of workers with direct family responsibilities who were eligible for maternity protection, or to take maternity, parental or compassionate leave during the reporting period.	%
	C31	Local capacity building	0.028		S-LCA22	Number of programmes targeting capacity building in the community during the reporting period.	programmes/FU
					S-LCA23	Number of people in the community benefitting from capacity building programmes during the reporting period.	persons/FU
	C32	Employment local community	0.028		S-LCA24	Number of new jobs created during the reporting period.	new jobs/FU
					S-LCA25	Number of jobs lost during the reporting period.	jobs lost/FU

Home web page



You have been invited here to help us in:

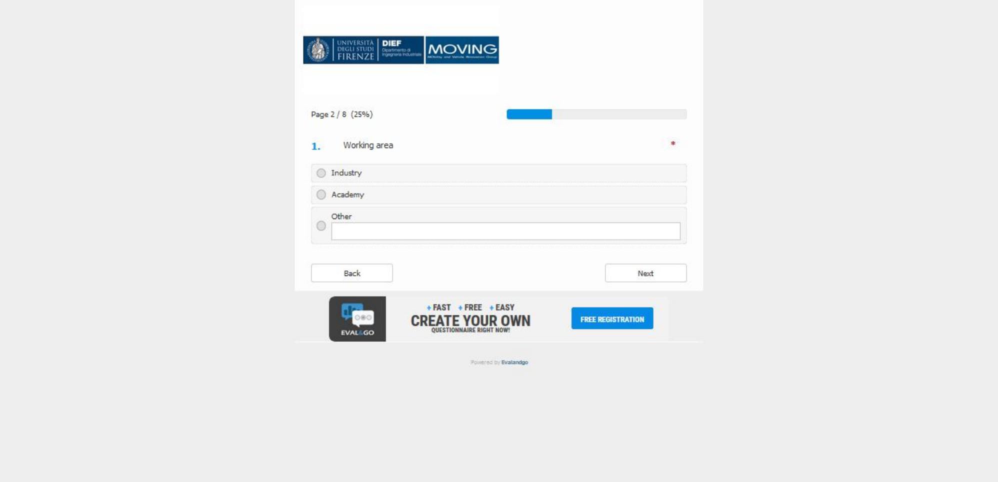
Prioritizing environmental, economic and social aspects in Life Cycle Sustainability Assessment

The Survey You are going to participate has been proposed by the MOVING UNIFI research group of the Department of Industrial Engineering, University of Florence (Italy).

MOVING UNIFI conducts research on topics related to vehicle engineering and Eco design.

Evaluating sustainability of products during an early phase and by taking into account the "three-pillar" concept - environment, economy and society – is one of our goal. In this sense, the Life Cycle Sustainability Assessment (LCSA), as the combination of LCA (environment), LCC (economy) and

Person description (1)



Page 2 / 8 (25%)

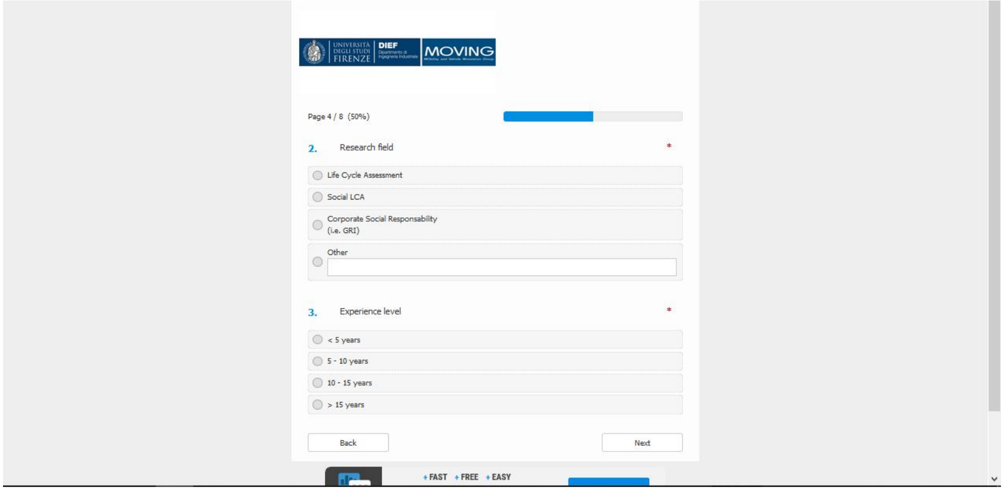
1. Working area *

○ Industry

○ Academy

○ Other

Person description (2)



Page 4 / 8 (50%)

2. Research field *

○ Life Cycle Assessment

○ Social LCA

○ Corporate Social Responsability (i.e. GRI)

○ Other

3. Experience level *

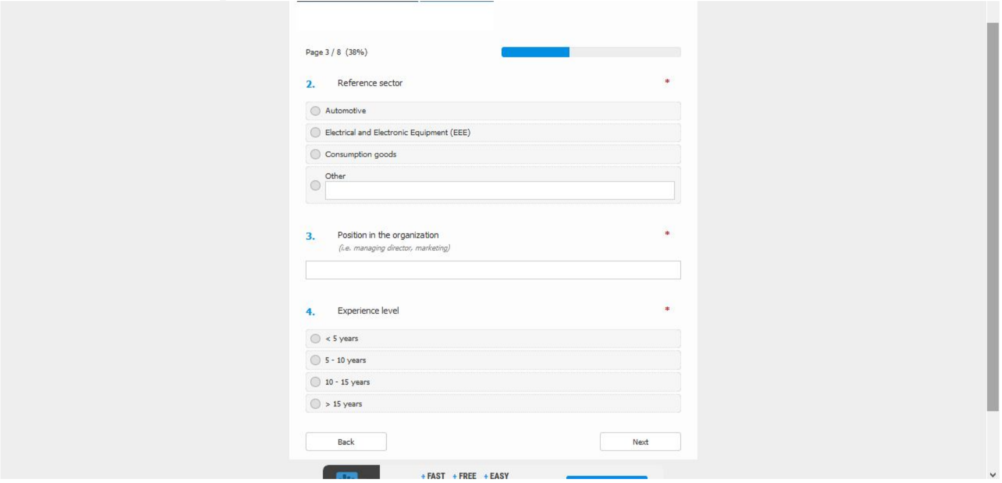
○ < 5 years

○ 5 - 10 years

○ 10 - 15 years

○ > 15 years

Person description (3)



Page 3 / 8 (38%)

2. Reference sector *

○ Automotive

○ Electrical and Electronic Equipment (EEE)

○ Consumption goods

○ Other

3. Position in the organization *
(i.e. managing director, marketing)

4. Experience level *

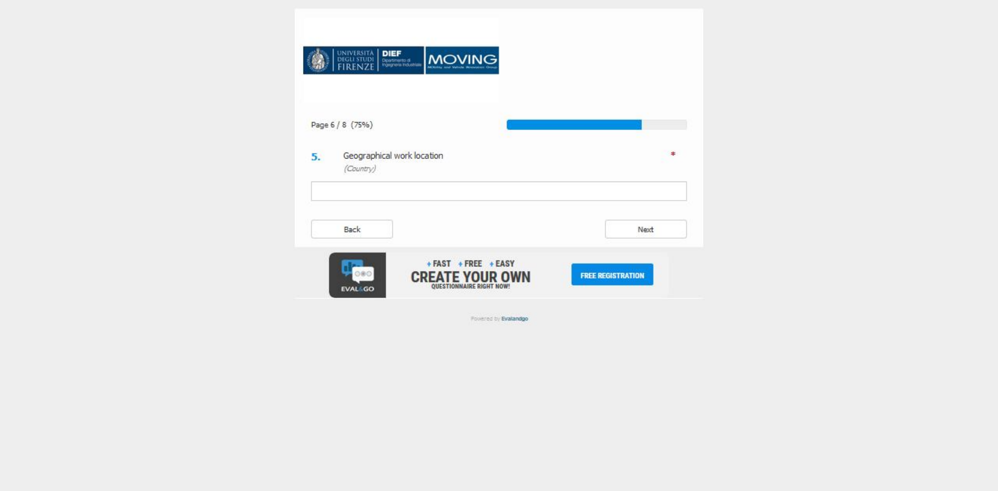
○ < 5 years

○ 5 - 10 years

○ 10 - 15 years

○ > 15 years

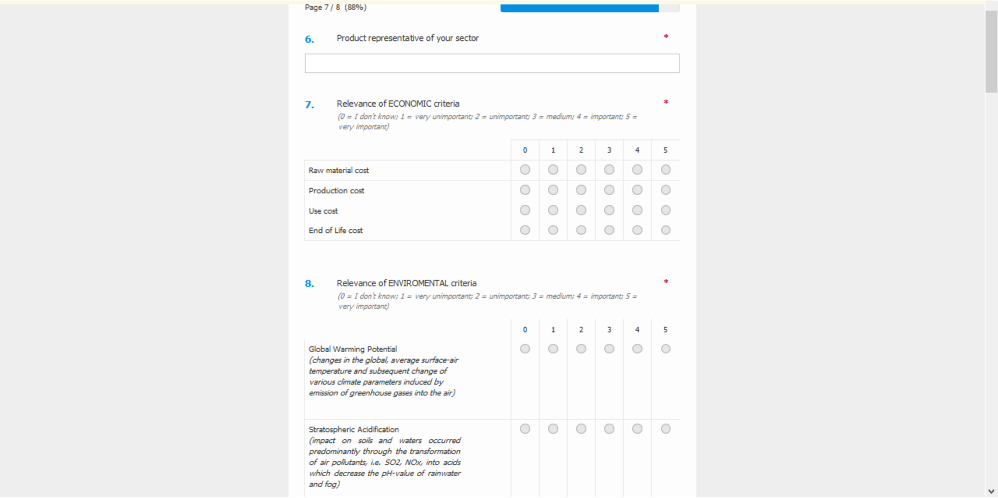
Person description (4)



Page 6 / 8 (75%)

5. Geographical work location *
(Country)

Product representative of the given sector and Relevance of economic, environmental and social criteria (1)



Page 7 / 8 (88%)

6. Product representative of your sector *

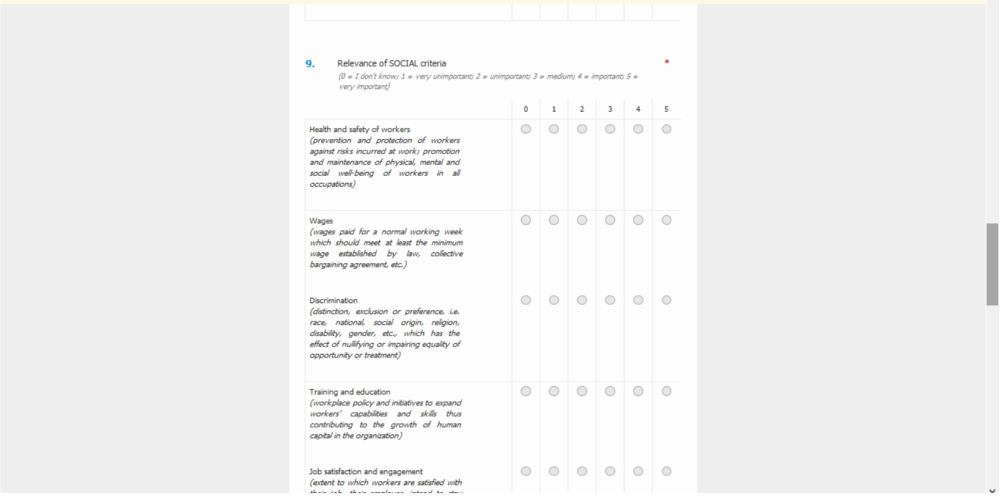
7. Relevance of ECONOMIC criteria *
(0 = I don't know; 1 = very unimportant; 2 = unimportant; 3 = medium; 4 = important; 5 = very important)

	0	1	2	3	4	5
Raw material cost	○	○	○	○	○	○
Production cost	○	○	○	○	○	○
Use cost	○	○	○	○	○	○
End of Life cost	○	○	○	○	○	○

8. Relevance of ENVIROMENTAL criteria *
(0 = I don't know; 1 = very unimportant; 2 = unimportant; 3 = medium; 4 = important; 5 = very important)

	0	1	2	3	4	5
Global Warming Potential *(changes in the global, average surface-air temperature and subsequent change of various climate parameters induced by emission of greenhouse gases into the air)*	○	○	○	○	○	○
Stratospheric Acidification *(impact on soils and waters occurred predominantly through the transformation of air pollutants, i.e. SO2, NOx, into acids which decrease the pH-value of rainwater and fog)*	○	○	○	○	○	○

Relevance of economic, environmental and social criteria (2)

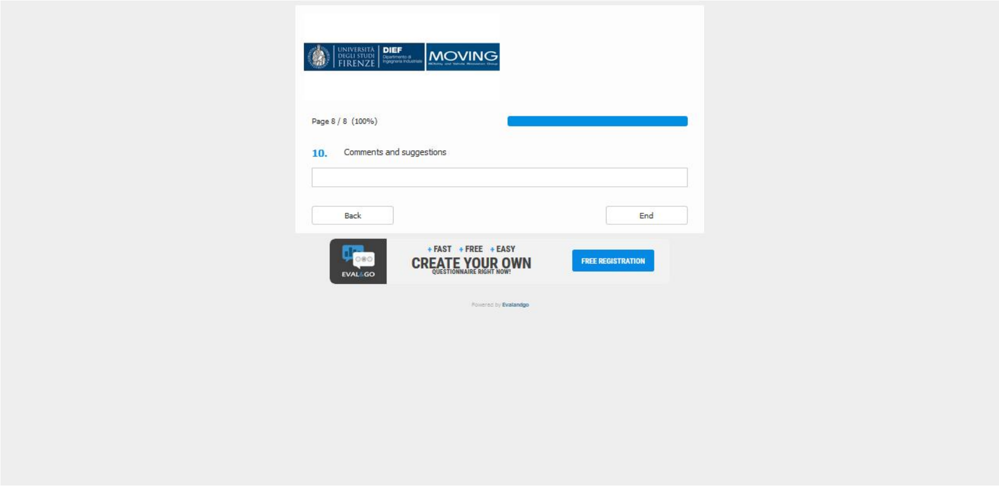


9. Relevance of SOCIAL criteria *

(0 = I don't know; 1 = very unimportant; 2 = unimportant; 3 = medium; 4 = important; 5 = very important)

	0	1	2	3	4	5
Health and safety of workers *(prevention and protection of workers against risks incurred at work; promotion and maintenance of physical, mental and social well-being of workers in all occupations)*	○	○	○	○	○	○
Wages *(wages paid for a normal working week which should meet at least the minimum wage established by law, collective bargaining agreement, etc.)*	○	○	○	○	○	○
Discrimination *(distinction, exclusion or preference, i.e. race, national, social origin, religion, disability, gender, etc., which has the effect of nullifying or impairing equality of opportunity or treatment)*	○	○	○	○	○	○
Training and education *(workplace policy and initiatives to expand workers' capabilities and skills thus contributing to the growth of human capital in the organization)*	○	○	○	○	○	○
Job satisfaction and engagement *(extent to which workers are satisfied with*	○	○	○	○	○	○

Comments and suggestions



Page 8 / 8 (100%)

10. Comments and suggestions

Annex D: S-LCA data for the case study 1

Allocated values LCSi

	Performance indicators	**Unit**	**Company A**	**Company B**	**Magneti Marelli**	**Car manufacturer**
Workers	Number of hours of health & safety training given during the reporting period.	hours	1.259	1.353	0.410	n.a.
	Average number of incidents during the reporting period.	Number	0.548	0.677	0	10.7
	Percentage of workers whose wages meet at least the legal or industry minimum wage and their provision fully complies with all applicable laws.	%	1%	100%	100%	100%
	Percentage of workers who are paid a living wage.	%	n.a.	0%	0%	100%
	Percentage of workers whose social benefits meet at least legal or industry minimum standards and their provision fully complies with all applicable laws.	%	0.06%	100%	100%	100%
	Percentage of workers who exceeded 48 hours of work per week regularly during the reporting period.	%	0%	0%	0%	0%

Workers	Number of hours of child labour identified during the reporting period.	hours	0	0	0	0
	Number of actions during the reporting period targeting business partners to raise awareness of the issue of child labour.	actions	0	0	0	0.018
	Number of hours of forced labour identified during the reporting period.	hours	0	0	0	0
	Number of actions during the reporting period targeting business partners to raise awareness of the issue of forced labour.	actions	0	0	0	0.018
	Number of complaints identified during the reporting period related with discrimination.	complaints	0	0	0	0
	Number of actions taken during the reporting period to increase staff diversity and/or promote equal opportunities.	actions	0	0.406	0	0.054
	Percentage of workers identified during the reporting period who are members of associations able to organise themselves and/or bargain collectively.	%	0.67%	46.00%	39.1%	n.a.
	Percentage of workers who have documented employment conditions.	%	100%	100%	100%	100%
	Number of hours of training per employee during the reporting period.	hours	0.007	2.030	0.769	n.a.

	Percentage of workers with direct family responsibilities who were eligible for maternity protection, or to take maternity, parental, or compassionate leave during the reporting period.	%	0.01%	8.03%	53.0%	21.0%
	Percentage of workers who participated in a job satisfaction and engagement survey during the reporting period.	%	0.39%	70.00%	89.4%	89.0%
	Worker turnover rate during the reporting period.	%	0.00%	1.26%	4.50%	0.50%
Local communities	Number of programmes during the reporting period to enhance community health and safety.	programmes	0.183	n.r.	n.r.	0.018
	Number of adverse impacts on community health or safety identified during the reporting period.	adverse impacts	0.000	n.r.	n.r.	0.018
	Number of programmes during the reporting period to enhance community access to tangible resources or infrastructure.	programmes	n.a.	n.a.	n.a.	n.a.
	Number of adverse impacts on community access to tangible resources or infrastructure during the reporting period.	adverse impacts	n.a.	n.a.	n.a.	n.a.
	Number of programs targeting capacity building in the community during the reporting period.	programmes	n.a.	n.a.	n.a.	n.a.

Local communities	Number of people in the community benefitting from capacity building programmes during the reporting period.	persons	n.a.	n.a.	n.a.	n.a.
	Number of programmes or events targeting community engagement during the reporting period.	programmes	0.366	1.488	0.439	0.536
	Number of new jobs created during the reporting period.	new jobs	0.000	1.218	0.000	0.000
	Number of jobs lost during the reporting period.	jobs lost	0.000	0.271	0.000	0.000

(n.a means not available; n.r means not relevant)

Aggregated values PLC

Performance Indicators	**Unit**	**PLC Indicator (formula excel)**	**PLC Indicator (formula handbook)**
Number of hours of health and safety training per worker given during the reporting period.	hours	1.096	0.952
Average rate of incidents during the reporting period.	number	1.036	0.900
Percentage of workers whose wages meet at least legal or industry minimum standards and their provision fully complies with all applicable laws.	%	0.520	0.520
Percentage of workers who are paid a living wage.	%	0.052	0.052
Percentage of workers whose social benefits meet at least legal or industry minimum standards and their provision fully complies with all applicable laws.	%	0.515	0.515
Percentage of workers who exceeded 48 hours of work per week regularly during the reporting period.	%	0.000	0.000
Number of actions during the reporting period targeting business partners to raise awareness of the issue of child labour.	hours	0.000	0.000
Number of hours of child labour identified during the reporting period.	actions	0.001	0.001

Number of actions during the reporting period targeting business partners to raise awareness of the issue of forced labour.	hours	0.000	0.000
Number of hours of forced labour identified during the reporting period.	actions	0.001	0.001
Number of actions taken during the reporting period to increase staff diversity and/or promote equal opportunities.	complaints	0.000	0.000
Number of complaints identified during the reporting period related to discrimination.	actions	0.130	0.113
Percentage of workers identified during the reporting period who are members of associations able to organise themselves and/or bargain collectively.	%	0.206	0.206
Percentage of workers who have documented employment conditions.	%	1.000	1.000
Numbers of hours of training per employee during the reporting period.	hours	0.754	0.655
Percentage of workers with direct family responsibilities who were eligible for maternity protection, or to take maternity, parental or compassionate leave during the reporting period.	%	0.115	0.115
Percentage of workers who participated in a job satisfaction and engagement survey during the reporting period.	%	0.401	0.401
Worker turnover rate during the reporting period.	%	0.011	0.011
Number of programmes during the reporting period to enhance community health or safety.	programmes	0.090	0.078
Number of adverse impacts on community health or safety identified during the reporting period.	adverse impacts	0.001	0.001
Number of programmes during the reporting period to enhance community access to tangible resources or infrastructure.	programmes	-	-
Number of adverse impacts on community access to tangible resources or infrastructure during the reporting period.	adverse impacts	-	-
Number of programmes targeting capacity building in the community during the reporting period.	programmes	-	-
Number of people in the community benefitting from capacity building programmes during the reporting period.	persons	-	-
Number of programmes or events targeting community engagement during the reporting period.	programmes	0.737	0.641
Number of new jobs created during the reporting period.	new jobs	0.382	0.331
Number of jobs lost during the reporting period.	jobs lost	0.085	0.074

Formula excel: all the indicators are aggregated by means of the formula

$$PLC_{indicator} = \frac{\sum_i LCSi_{indicator\ product\ allocated}}{\sum_i LCSi_{hours}}$$

Performance values interpretation

Performance indicators	**unit**	**Without allocation**			**With allocation**		
		RV	**PV 1**		**RV**	**PV 1**	
Number of hours of health and safety training per worker given during the reporting period.	hours	1	-0.048	negative performance	0.87	0.083	positive performance
Average rate of incidents during the reporting period.	number	0	-0.900	negative performance	0	-0.900	negative performance
Percentage of workers whose wages meet at least legal or industry minimum standards and their provision fully complies with all applicable laws.	%	1	0.520	positive performance	1	0.520	positive performance
Percentage of workers who are paid a living wage.	%	1	0.052	positive performance	1	0.052	positive performance
Percentage of workers whose social benefits meet at least legal or industry minimum standards and their provision fully complies with all applicable laws.	%	1	0.515	positive performance	1	0.515	positive performance
Percentage of workers who exceeded 48 hours of work per week regularly during the reporting period.	%	0	0.000	target or minimum scenario has been reached	0	0.000	target or minimum scenario has been reached
Number of hours of child labour identified during the reporting period.	hours	0	0.000	target or minimum scenario has been reached	0	0.000	target or minimum scenario has been reached

Performance indicators	**Unit**	**Without allocation**			**With allocation**		
		RV	**PV 1**		**RV**	**PV 1**	
Number of actions during the reporting period targeting business partners to raise awareness of the issue of child labour.	actions	1	-0.999	negative performance	0.87	-0.868	negative performance
Number of hours of forced labour identified during the reporting period.	hours	0	0.000	target or minimum scenario has been reached	0	0.000	target or minimum scenario has been reached
Number of actions during the reporting period targeting business partners to raise awareness of the issue of forced labour.	actions	1	-0.999	negative performance	0.87	-0.868	negative performance
Number of complaints identified during the reporting period related to discrimination.	complaints	0	0.000	target or minimum scenario has been reached	0	0.000	target or minimum scenario has been reached
Number of actions taken during the reporting period to increase staff diversity and/or promote equal opportunities.	actions	1	-0.887	negative performance	0.87	-0.756	negative performance
Percentage of workers identified during the reporting period who are members of associations able to organise themselves and/or bargain collectively.	%	1	0.206	positive performance	1	0.206	positive performance
Percentage of workers who have documented employment conditions.	%	1	1.000	target or minimum scenario has been reached	1	1.000	target or minimum scenario has been reached
Numbers of hours of training per employee during the reporting period.	hours	1	-0.345	negative performance	0.87	-0.214	negative performance

Performance indicators	**Unit**	**Without allocation**			**With allocation**		
		RV	**PV 1**		**RV**	**PV 1**	
Percentage of workers with direct family responsibilities who were eligible for maternity protection, or to take maternity, parental or compassionate leave during the reporting period.	%	1	0.115	positive performance	1	0.115	positive performance
Percentage of workers who participated in a job satisfaction and engagement survey during the reporting period.	%	1	0.401	positive performance	1	0.401	positive performance
Worker turnover rate during the reporting period.	%	0	-0.011	negative performance	0	-0.011	negative performance
Number of programmes during the reporting period to enhance community health or safety.	programmes	1	-0.922	negative performance	0.87	-0.791	negative performance
Number of adverse impacts on community health or safety identified during the reporting period.	adverse impacts	0	-0.001	negative performance	0	-0.001	negative performance
Number of programmes during the reporting period to enhance community access to tangible resources or infrastructure.	programmes	1	-	0.000	1	-	0.000
Number of adverse impacts on community access to tangible resources or infrastructure during the reporting period.	adverse impacts	0	-	0.000	0	-	0.000

Performance indicators	**Unit**	**Without allocation**			**With allocation**		
		RV	**PV 1**		**RV**	**PV 1**	
Number of programmes targeting capacity building in the community during the reporting period.	programmes	1	-	0.000	1	-	0.000
Number of people in the community benefitting from capacity building programmes during the reporting period.	persons	1	-	0.000	1	-	0.000
Number of programmes or events targeting community engagement during the reporting period.	programmes	1	-0.359	negative performance	0.87	-0.228	negative performance
Number of new jobs created during the reporting period.	new jobs	1	-0.669	negative performance	0.87	-0.537	negative performance
Number of jobs lost during the reporting period.	jobs lost	0	-0.074	negative performance	0	-0.074	negative performance