Alma Mater Studiorum – Università di Bologna

DOTTORATO DI RICERCA IN

Ingegneria Civile, Chimica, Ambientale e dei Materiali

Ciclo XXXI

Settore Concorsuale di afferenza: 08/A2
Settore Scientifico disciplinare: ING-IND/29

Comprehensive examination of automotive product impact
A look ahead in light of sustainable development challenges: the Magneti Marelli S.p.a business case.

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Esame finale anno 2019

To my beloved parents
Giovanni and Mirella,
...my great mentors,
In both my personal
and daily life.

Principle 1 – “Human beings are at the
centreof concerns for sustainable
development. They are entitled to a healthy
and productive life in harmony with
nature”.
(Rio Declaration – UNCED, 1992)

“You must be the change you wish to see in
the world”.
*(*Mahatma Gandhi)

“In the 21st century, I think the heroes will
be the people who will improve the quality
of life, fight poverty and introduce more
sustainability”.
(Bertrand Piccard)

DECLARATION

The present thesis is the result of my individual work and does not include third party work apart from what is specifically indicated in the manuscript. This full dissertation has not been formerly submitted to the public, with the exception of specific parts which have been submitted to specific journals which are explicitly indicated in the text.

ABSTRACT

Sustainable development imperatives drive industrial selection in the field of product development. Indeed, automotive productiveness plays a key-role in the worldwide trend for the transition towards a more environmentally friendly, economically affordable and socially sustainable balance. In the last few years automotive industry has been rapidly changed due to the increasingly concerned about resource depletion and GHG emissions generation. In this framework, actions addressed to reduce automotive impact has increased. To meet environmental improvement expectation vehicle mass has been progressively reduced over the time, promoting structure and layout optimization via mass decrease and reformulation. The lightweighting can be achieved with different and combined strategies: variation of materials and technology, which should occur at early product design stage. Nonetheless, a new design mind-set formula is necessary to integrate environmental attribution to component characteristic: the life cycle thinking as a holistic approach, which take into account the product life cycle. In this way, the selection of design for environment strategy is based on a balance between technological, manufacturing and sustainability aspect without shifting environmental consequences beyond company area. To meet environmental improvement expectation, Magneti Marelli© Spa as a part of automotive sector has started to be committed on sustainability programs in order to reduce the impact caused by its product on the environment. Drive by those requirements during research and development stage the Company makes effort in order to guarantee a sustainable product harmonizing product functional requirement with properties of eco-compatibility. Moreover, Magneti Marelli has faced the challenge of balancing the three factors of sustainable development from the corporate to the product level by implementing new industrially engineered methodologies to monitor their activities. For this purpose, the Company adopted a methodology, modeled on proposals made by scientific institutes, for the creation of its own system, devoted to obtaining and presenting results for a strategic plan with regard to its products, which is measurable, understandable and implementable. The well-recognized Life Cycle Sustainability Assessment LCSA methodology was used and adapted to the company's context for R&D applications and purposes. This effort was accomplished with the collaboration of company members at different levels (R&D, purchase, logistics, innovation) and with the stakeholders' collaboration (suppliers of materials and semi-products, EoL management companies and vehicle users) and resulted in over fourteen projects which introduced a wide array of innovative materials, processes and technological applications. The outcome of these projects have enriched the company's knowledge and have become the basis for more conscious and strategic choices for achieving goals relating to a reduction in product impact, , thus helping to protect the planet while guaranteeing company development and progress.

Key words: sustainable development, automotive, LCSA, product innovation.

ACKNOWLEDGEMENTS

I would like to thank Professor Alessandra Bonoli, my academic advisor, for all the support she gave me during all three years I spent carrying out my PhD research objectives. She gave me the opportunity to work on a stimulating theme, which is increasingly gaining ground in the worldwide scenario and which has made me passionate about the present research topic. Thank you for all the advice and support received and for all the words of encouragement.

My gratitude for the outcome goes to my company co-advisor Rubina Riccomagno. She was my company guide directing my work and allowing me to collaborate with all the people concerned. She enabled me to become an integral part of the Marelli world, fully involving me in all the activities of interest for my research project. Despite the physical distance involved and her numerous commitments, she always found time to support my research activities and helped me by responding to all my questions. Thank you for always being present, especially during the intense period of your motherhood. Working in your team has made me grow a lot, both professionally and personally.

Heartfelt thanks to my family: especially my dad Giovanni. You are my life-coach, my most persevering supporter. You have taught me to believe in and seek a better world, and that even difficult things can be achieved by making use of the necessary tools: self-sacrifice and self-confidence. Thank you for teaching me the meaning of sacrifice, respect and work. Thank you for encouraging the growth of this awareness in me.

My gratitude goes to all the staff and management of Magneti Marelli for the warmth with which I was welcomed into the company, and for the serene and pleasant atmosphere that accompanied my experience in the work environment. In particular, I would like to give special thanks to the R&D members (located in Bologna) of the "Throttle Bodies & Actuators" who hosted me during these three years: above all to Dr. Ing. Marcello Colli who allowed me to carry out my activity in this wonderful team.

A sincere thanks goes to my first teacher, Helen Ball. I was 5 years old when you welcomed me as your student for English lessons and even today you are always there to correct my blunders. Thanks for spending hours and time reviewing all the grammar with me. I really do not know how would I manage it without her.

Lastly, I would like to thank my PhD colleagues for being such united and supportive classmates. And a real word of appreciation is for Francesca, my “Ciccia Pasticcia” my Jiminy Cricket. Thanks for always being close, a super friend, I have found a sister in you!

LIST OF ABBREVIATIONS AND ACRONYMS

ACEA	Automobile Manufacturers’ Association
$\mathrm{ADP}_{\mathrm{elements}}$	Abiotic Depletion elements
$\mathrm{ADP}_{\mathrm{fossil}}$	Abiotic Depletion fossil
AIM	Air Intake Manifold
AP	Acidification Potential
BEV	Battery electric vehicles
BP	Brake Pedal
CM	Crossmember
DfE	Design for Environment
DSB	Dashboard
EC	European Commission
EEA	European Automobile Agency
EP	Eutrophication Potential
FAETP	Freshwater Aquatic Ecotoxicity Potential
FU	Functional Unit
GWP	Global Warming Potential
HTP	Human Toxicity Potential
ILCD	International Reference Life Cycle Data System
ISO	International Standard Organization
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSM	Life Cycle Sustainability Management
MAETP	Marine Aquatic Ecotoxicity Potential
MCDM	Multiple-criteria decision Making
ODP	Ozone Layer Depletion Potential
PBS	Pedal box Support
PED	Primary Energy Demand
POCP	Photochemical Ozone Creation Potential
PSS	Product Service System
RE	Reflector
SA	Suspension Arm
SETAC	Society of Environmental Toxicology and Chemistry
SLCA	Sustainable Life Cycle Assessment
TB	Throttle Body
TETP	Terrestrial Ecotoxicity Potential
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
UNEP	United Nations Environmental Programme

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"In order to carry a positive action we must
develop here a positive vision".
(Dalai Lama)

In recent decades, the exponential increase of the population together with an increase in well-being and wealth has caused a significant increase in "global consumption." Undoubtedly, our society inflicts huge stress upon the earth. Climate change, resource scarcity and pollution are only some of the consequences of human activities on the environment. Certainly, a drastic change in human habits is needed to preserve and support the planet. Unfortunately, the world has only a limited number of resources, mineral, metal and abiotic and the current demand for them exceeds what is available from the earth. Furthermore, the regeneration of resources does not follow a rhythm that allows for their recreation within the time necessary for arriving at an equilibrium between supply and demand. The current model creates imbalances, which weigh on economic growth and have environmental repercussions.

An urgent response from governments and industry is necessary to reduce human impact. In this regard, the Rio Declaration on Environment and Development states:

'*To achieve sustainable development and a higher quality* of life f*or all people, States should reduce and eliminate unsustainable patterns of production and consumption*…'

Within this framework, three important factors should be considered in the application of sustainable development principles: balance between environmental, economic and social aspects, in view of a life cycle thinking (LCT) approach. For these reasons, the concept of "sustainable development" has as its basis the aim of reducing the gap between excessive demand and means of supply, without limiting social and economic well-being. To this end, the "linear" consumption system is to be considered obsolete and superseded by an innovative formula consisting in the design of a "circular economy" based on the revaluation of resources and the maximum reduction of environmental waste. In order to achieve this synchrony, the whole world (governments, people and industries) is striving to create a harmonious and global "sustainable development".

There are numerous challenges to be faced in achieving the aforementioned objectives and some fundamental research questions are:

- How can we predict models for sustainable development?
- In essence, how should we collaborate to increase economic efficiency towards the circular economy model?
- How can expertise disseminate these concepts worldwide and root them in the mindset of individuals?
- How is it possible to balance increasingly advanced technology with respect for the environment? In this context what is the role of technology?
- What are the key challenges for a sustainable manufacturing industry?

To try to answer these questions, experts in the field, researchers and scientists, in collaboration with governments, have tried to identify successful circular business models to determine which factors allow for potential success and which sectors and products hold the greatest potential for circularity, especially the critical factors in each sector and where improvements can be made. Companies have found that the benefits created by the implementation of a circular economy translate into a reduction of waste and natural resources and also entail economic savings.

These models must be organized with foresight and reliability so as to inspire confidence because of the many possible conflicting risks and objectives (especially economic and environmental ones).Conflicting goals often require compromise. In this context, a series of initiatives and regulations have been started up to moderate the effects of manufacturing activities.

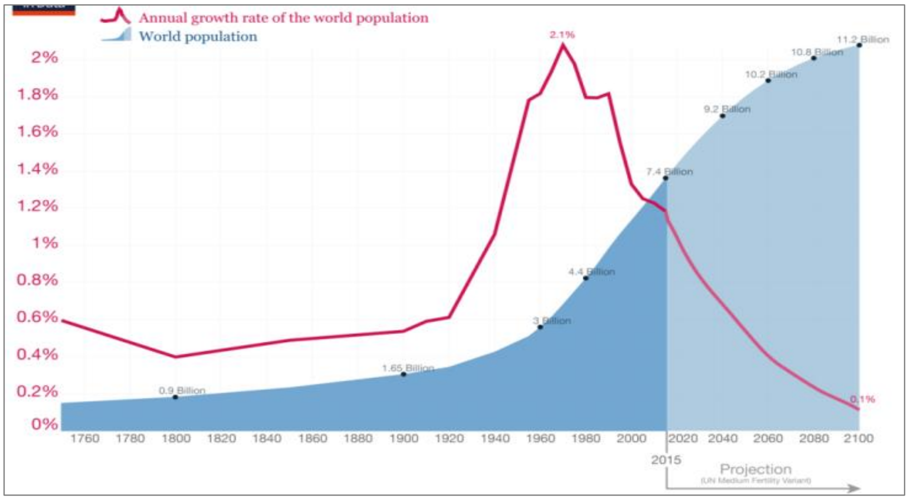
1.1 GLOBAL CHALLENGES TO SOCIETY, THE ENVIRONMENTAND THE ECONOMY

Record temperatures in recent years, along with natural disasters, are gaining the attention of the media and are making the public increasingly conscious of climate change with its possible consequences. Population growth, together with an increase in economic welfare, has brought about rapid industrial development leading to overwhelming advances in technology at the expense of the environment. The world is evolving at ever-increasing rates and several factors have been causing environmental disasters never experienced previously. Projections for the future warn that if this exploitation and excessive industrialization of the environment are not remedied, the earth will no longer be able to provide for our needs as they are at the present time.

1.1.1 POPULATION GROWTH

Among the factors responsible for all this, undoubtedly the continuous growth in the world's population is the primary cause for worry. The graph, depicted in Figure 1,showsthe annual population growth rate for the total world population considering the time lapse1750-2010, with future projections up to 2100. It has been projected that by 2100 the global population will have risen to over 11.2 billion. The 20th century is the period in history when the most drastic changes in population growth occurred. Over the first 50 years of the 20th century, annual growth increased by up to 2.1% (before this, it was well below 1%). Subsequently, the growth rate has been steadily decreasing, with projections estimating an annual rate of 0.1% for 2100.This means that the world population will have doubled from its present level by the end of the 21st century(Our World in Data, 2017).

Figure 1 – World population growth [Our World in Data, 2017].



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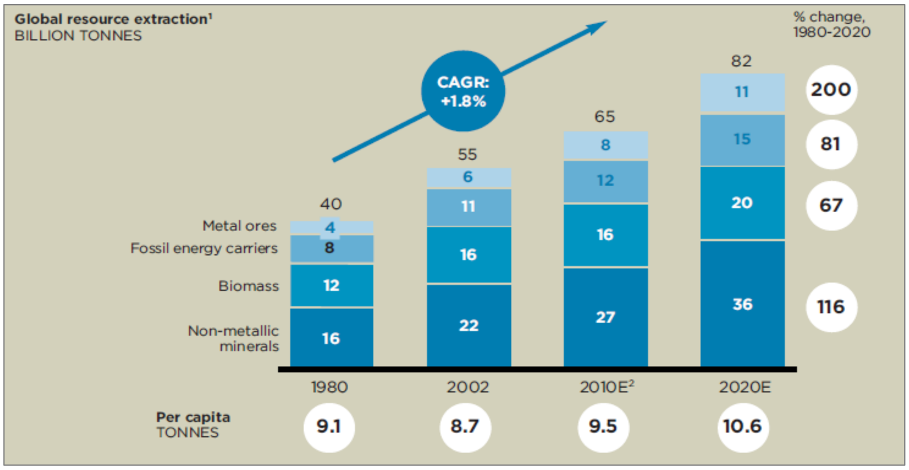
This predicted rapid population increase presents serious concerns regarding emissions and the resources needed for a sustainability plan.

1.1.2 THE DEPLETION OF RESOURCES

The following illustration presents the amounts of resources extracted worldwide entering the economic system, registered from 1980 to the present day with projections up to 2020. Biogenic and non-biogenic materials are included, as well as materials used to produce energy and others used in production processes. Overall extractions are expected to grow to 82 billion tonnes by 2020.

Figure 2 – Amounts of extracted resources entering the economic system and forecast(Ellen MacArthur Foundation, 2013).



Huge amounts of resources are needed in the production of materials (especially virgin materials) and/or energy, especially electricity. Through the incineration of selected discarded products (materials) a small share of energy (generally steam or electricity) can be recovered, whereas the reuse and production of secondary materials, saves much more energy. Considerable energy consumption can be avoided with a system that relies less on upstream production, i.e. the use of secondary materials. To this end industries have been quite determined in achieving upper recycling rates.

1.1.3 WASTE GENERATION

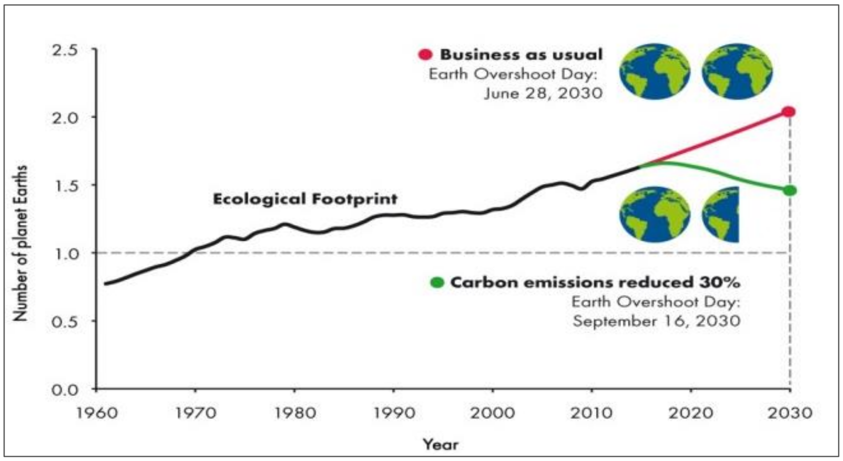
In a linear management system, the waste disposal to landfill means the loss of its residual energy. But this is not the only problem caused by waste production. In fact, the waste of a great part of materials occursbetween mining and final manufacturing. The damage caused by the excessive dumping of products is double: in addition to the generation of waste in resources, they are burdensome once degraded, for example products containing dangerous substances (E-Waste, House Hazardous Waste) such as electrical equipment or the used liquids of disused machinery.

1.1.4 HARMFUL EMISSIONS AND DISCHARGES

Another serious problem that afflicts the environment and, above all, living beings and people, is the damage caused in the climate and ecosystem by the release into the environment of dangerous substances, especially chemical substances (i.e. formaldehyde, mercury, lead, hazardous/toxic air pollutants, polychlorinated biphenyls (PCBs) and pesticides). Harmful substances can be solid, liquid and also gases. The latter in particular are one of the most harmful substances as regards air contamination: pollutants include sulphur dioxide (SO_2), oxides of nitrogen (NO_x), ozone (O_3), carbon monoxide (CO), volatile organic compounds (VOCs), certain toxic air pollutants and some gaseous forms of metals. Moreover, other particles, such as PM2.5 and PM_{10}, include a mixture of harmful substances like: sulphates, nitrates, elemental (black) carbon, organic carbon and crustal material. Some pollutants are directly released into the atmosphere while others are indirectly generated from chemical reactions. Other dangerous emissions are generated at ground-level, suchas NO_x and VOCs, which react with the sunlight. Toxic substances affect human life and the environment through different vehicles: land, air and water contamination. When the water (rivers, lakes, and oceans) becomes polluted, it can endanger wildlife and indirectly have repercussions on human beings. However, the most damaging impact seems to be caused by greenhouse gases (GHG), which, among anthropogenic activities, have seen a sharp increase. Apart from this, agricultural activities, deforestation, and excessive land-use have been recognized as the second-largest contributors (Boden et al., 2017).

It is believed that anthropogenic greenhouse gas emissions are mainly responsible for the recorded climate change, which has caused a notable warming of the Earth's surface, with CO_2 playing the most prominent role. In 1997, numerous countries voted for the Kyoto Protocol, which aims at setting targets for the control of industrial activities in order to reduce CO_2emissions. A concept that helps to understand the balance and impact of human activity on earth is that of the Ecological Footprint, which is a metaphor used to portray the amount of resources (i.e. land and water) that individuals would hypothetically need to provide for vital resources and to absorb their waste. In fact, the Ecological Footprint (Global Footprint Network Advancing the Science Sustainability, 2018) measures the ecological assets a population requires to satisfy their needs and calculates the rate of human consumption compared with the re-generation of nature. When a population Footprint exceeds the earth's bio-capacity to regenerate and absorb human activities, an ecological deficit is encountered. The bio-capacity is the availability of the Earth's resources to meet human demands. Today humanity uses the resources of the equivalent of 1.5 of our planet to provide for our needs and absorb waste. This means it now takes the Earth one year and four months to regenerate what people use up in a year. The Earth Overshoot Day is the day on the calendar when humanity uses up the resources it has taken the planet a full year to regenerate. This was calculated to take place on August 2nd 2017 (Figure 3).

Figure 3 – Ecological footprint trend from 1960 to 2030(Global Footprint Network Advancing the Science Sustainability 2018).



1.2 SUSTAINABLE DEVELOPMENT

Sustainable development has become a widespread concept. The main objective of *Sustainable Development* is to find a solution in order to *"meet the needs of the present without compromising the ability of future generations to meet their own needs*" (Bruntaland, 1987).

The main concern is related to the reduction of the impact of human activity on the environment, while guaranteeing the welfare of the population. For these reasons the solutions put forward for sustainable development must integrate economic, environmental and social dimensions in the creation of an effective added value. Sustainable development took its first steps in the '70s and'80s, with a growing awareness that the production and consumption models of industrialized societies were not compatible with the environment, but would soon cause the collapse of natural systems. A solution had to be found in order to reconcile economic growth with an equitable distribution of resources, for a development that did not compromise the needs of future generations. To better explain the objectives and strategies of sustainable development, reference should be made to the terms that make up the concept. 'Sustainability' means the preservation over time of existing conditions without causing damage to them. The second term 'development' is a concept with a broader meaning; this term refers to all the changes in the economic, social, institutional and political structures aimed at a continuous improvement in the field of industrial production. By combining both concepts, we obtain a global vision of what it means to improve the quality of life or well-being in a lasting way. The Word Commission on Environment and Development (Bruntaland, 1987) has given the following definition:

"*Sustainable development, far from being a definitive condition of harmony, is rather a process of change such that the exploitation of resources, the direction of investments, the orientation of technological development and institutional changes are made coherent with future needs beyond that with the current ones ". One aspect deserves to be highlighted, namely the centrality of the "participation of all.*"

The fulfillment of essential needs requires not only a new era of economic growth [...] but also the guarantee that these poor people have their fair share of the necessary resources [...] such equity should be assisted by both political systems, which ensure the effective participation of citizens in the decision-making process". The concept of sustainable development is based on a fundamental principle, that the economic and social dynamics for development must be compatible with the improvement of living conditions and the capacity of natural resources to regenerate in accordance with this development.

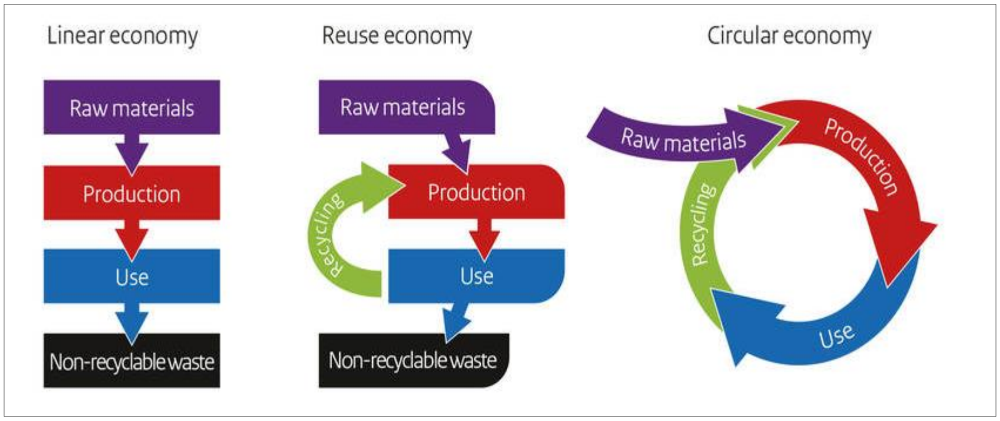
In 2015, various countries adopted the Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDGs) which are made up of 169 targets (Figure 4). Governments, businesses and civil society (from 193 countries) together with the United Nations are committed to achieving the Sustainable Development Agenda by 2030. To succeed in implementing efficiently the Sustainability programmers, it is essential to harmonize three core elements: economic growth, social inclusion and environmental protection. The global indicator is to be settled by the Inter Agency and Expert Group on SDG Indicators (IAEA-SDGs) and will then be approved by the Economic and Social Council and the General Assembly.

Figure 4 - Sustainable Development Goals(United Nation, 2015).

1.3 TRANSITION TO THE CIRCULAR ECONOMY

Our current consumption habits are not helping our current linear economy, which is based on the "take-make-dispose" concept. A possible solution for decreasing waste and preserving materials and energy is the strategy of re-use through recycling processes. As far as is conceivable, the most effective tactic is what has been called the "circular economy" where the resources value is preserved for as extensive as possible and the generation of waste are minimized" (European Commission, 2015). The three models are expressed in Figure 5.

Figure 5- Diagram of the concepts of the linear economy, re-use economy and circular economy.



The conceptual message of the circular economy is widespread today and transmits a very powerful message. Its a proven strategy for the better management of resources and aims at the minimization of waste and even its cancellation altogether, being based on the principles of the restorative circular economy. Thus, the old system of a linear economy, summarized by "take, create, and dispose", that is "extract, produce and, in the end, discard", has been demonized and abandoned in favor of a closed-cycle economy, subverting the "open" linear one and implementing the principles of sustainable development which are based on the awareness that resources are not unlimited but are destined to run out. From this consideration comes the concept of the "circular economy", defined by Janez Potočnik, Commissioner for the Environment, who, when presenting the EU objectives on recycling, expressed it in this way:

"*In the twenty-first century, characterized by emerging economies, millions of consumers belonging to the new middle class and interconnected markets still use linear economic systems inherited from the nineteenth century. If we want to be competitive we have to make the most out of our resources, putting them back in the production cycle instead of putting them in a landfill as waste*"(European Commission, 2014).

Therefore, the circular economy changes the rules regarding the use of resources so that, for example, the waste from an asset becomes a resource in a new production process and products are designed considering their possible repair and re-use (design for assembly or disassembly).The concept is characterized, more than defined, as an: “Economy that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles. It is conceived as a continuous positive development cycle that preserves and enhances natural capital, optimizes resource yields, and minimizes system risks by managing finite stocks and renewable flows. It works effectively at every scale. This economic model seeks to ultimately decouple global economic development from finite resource consumption”(BS 8001:2017, 2017).

In order to effectively implement the concept of a circular economy, changes must be made along the entire product value chain, starting from the design to its disposal. To do this it is essential to create synergies between technology and management within the same company and also between the various actors in the chain, the stakeholders (which will then give life to the concept of "industrial symbiosis"). It is not always possible to apply the result of zero rejection, there is always an element of linearity, considering that the demand for virgin resources cannot be completely stopped and that it is not always possible to recycle a material or recycle it completely. However, the concept of “circular economy” re-formulates the concept of “end of life” so as to promote re-use and/or restoration in order to reduce waste, as much as possible, beyond system boundaries. Such an economy is based on a few simple principles, which drive clear-cut sources of value creation. First and foremost, the minimization of excess, eradicated in the concept of ‘design out’ waste: components are designed and produced for a cycle of disassembly and re-use. Secondly, circularity introduces the differentiation between the consumable (made of biological ingredients) and durable (artificial) components of a product. The latter should be designed for their re-use. Finally, the energy required to fuel the product life cycle should be renewable by nature.

1.4SUSTAINABLE MANUFACTURING

Over the years, the concept of production has undergone considerable upheaval (Figure 6) in consideration of the most recent projects, which have emerged in terms of sustainability. These principles have been absorbed within the industry and above all in the manufacturing sector. One of the keys to achieving a circular economy project is undoubtedly the introduction of the logic of sustainability within the plants. In this regard, the concept of "industrial sustainability" envisages obtaining a competitive advantage by increasing the efficiency of the use of resources, promoting the reduction of waste and the maximization of environmental and social respect, compatible with economic optimization. Thus, since the introduction of the concept of the circular economy, the principle that has guided the choices of sustainable production has been 3R: reduce, re-use and recycle, aimed at optimal production using few resources while minimizing pollution. Nowadays the challenge is to develop the circular economy through sustainable manufacturing with the inclusion of the 6R principles (reduce, re-use, recycle, recover, redesign and remanufacture), to endorse sustainable manufacturing and enabling closed-loop and multiple life-cycle material flow (Figure 7).Sustainable production is of course a difficult process to implement because it is systemic and complex; in fact, it is necessary to consider essentially three levels of integral interaction: products, processes and systems. Generally speaking, sustainable production is founded on the circular economy and does not include precise references or specializations by sector, but rather guidelines and correct actions, to help achieve the objectives, due also to the complexity that lies in the interconnection between product, process and system. Sustainable production is not the prerogative of technology, which must maintain different level, especially with the looming of the 4.0 industry, but that of the integrated and holistic management of functional products with lower environmental, economic and social impact. Returning to the 6R concept, this methodology proposes a closed loop system. *Reduction* refers to the use of resources, both of materials and energy, as well as others during the production phase and the decrease in emissions and waste during the use phase. Another basic concept is that of *"re-using*" the component as a whole or its sub-parts. Thirdly, "*recycling*", is the process of transforming materials, which would otherwise be considered waste, into new materials or products. The *redesign* activity involves redesigning products by providing for the use of materials and resources recovered from the preceding life cycle. Another expedient is *re-manufacture* which provides for the re-elaboration of products already used in order to restore them to their original state or create a new form through the re-use of the largest number of parts possible without loss of functionality. The implementation of sustainable production principles and practices must emphasize not only the design phase but also the development and implementation of innovative and advanced production processes for production. In this way, sustainable production has been acknowledged as the engine of innovation in the industrial manufacturing sector.

Figure 6 - Evolution of manufacturing concept: from open loop to closed-loop lifecycles(Badurdeen f. and Jawahir I.S., 2016).

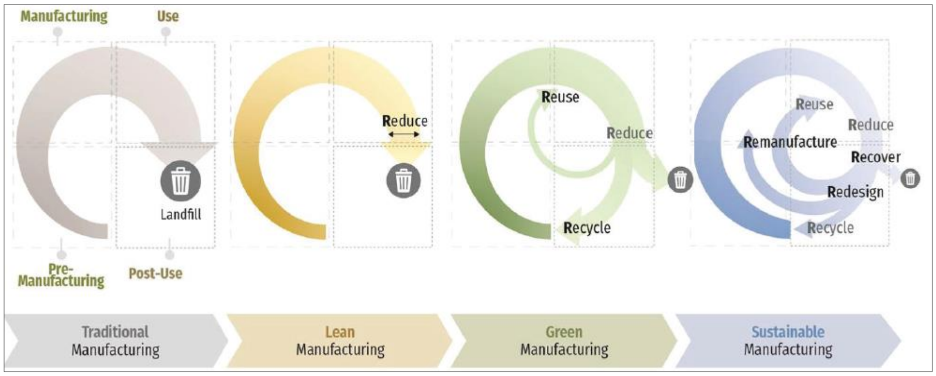
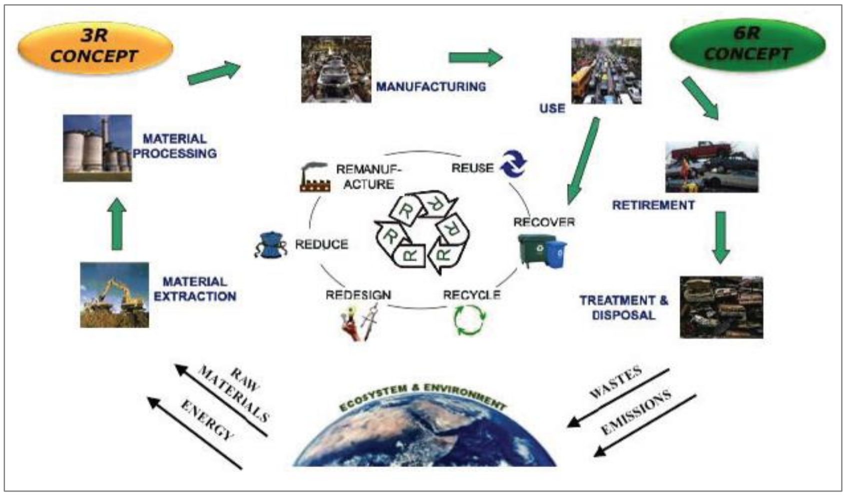
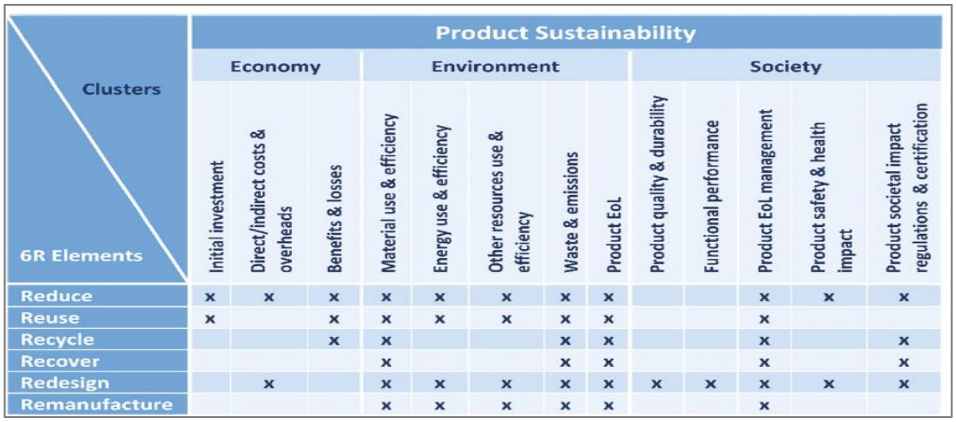


Figure 7–Explanation of 3R to the 6R concept(Jaafar I.h. et al., 2007).



Sustainable manufacturing will undoubtedly empower respect for the environment, together with economic growth and social well-being as a base for establishing sustainable value. A summary of possible approaches (metrics)to be used as reference in the adoption of the 6R methodology as applied to product sustainability in each of its dimensions (cluster areas) can be found in Figure 8.

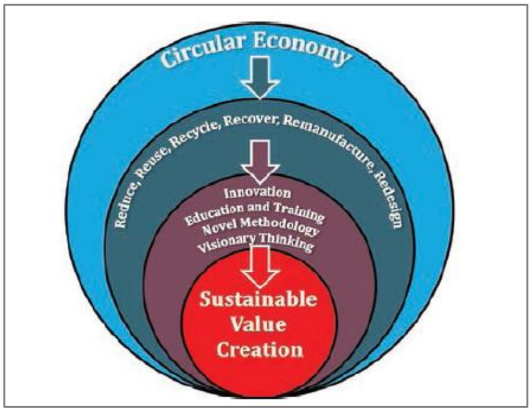
Figure 8–6R application in product sustainability cluster areas(Hapuwatte B.M. et al., 2017).



Clusters / 6R Elements	Product Sustainability												
	Economy			Environment					Society				
	Initial investment	Direct/indirect costs & overheads	Benefits & losses	Material use & efficiency	Energy use & efficiency	Other resources use & efficiency	Waste & emissions	Product EoL	Product quality & durability	Functional performance	Product EoL management	Product safety & health impact	Product societal impact regulations & certification
Reduce	×	×	×	×	×	×	×	×			×	×	×
Reuse	×		×	×	×	×	×	×			×		
Recycle			×	×			×	×			×		×
Recover				×			×	×			×		×
Redesign		×		×	×	×	×	×	×	×	×	×	×
Remanufacture				×	×	×	×	×			×		

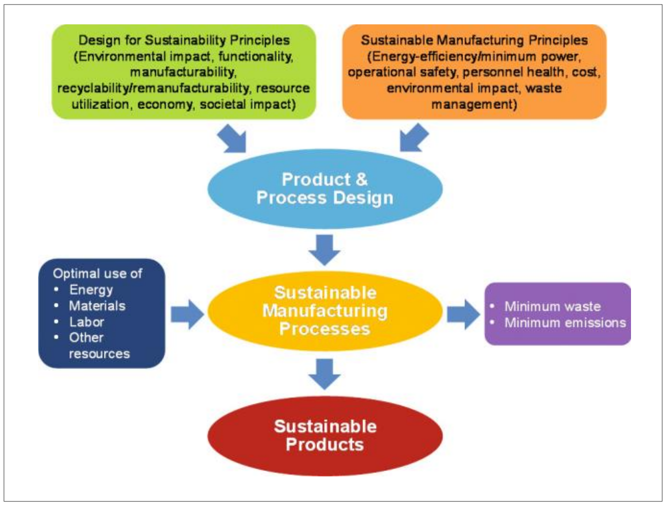
To give an example of the links and the relationships between the various concepts and how they are distributed according to the logic of their definitions, Figure 9has been provided. This illustrates how the thinking of the circular economy, based on the principles of 6R, influences the concept of sustainable manufacturing. In this sense industrial engineering (IE) can demonstrate how sustainable manufacturing (SM), embedded in the value creation of industry, overcomes the traditional single paradigms of management and technology.

Figure 9–Circular economy in the concept of sustainable value creation.



One of the most crucial phases in the application of sustainable manufacturing is the design of new products. Numerous elements are involved and it is difficult to manage multiple objectives (customers' requirements, functional restrictions and the enhancement of total life-cycle sustainability) and find worthwhile trade-off. A comprehensive evaluation of sustainability is insufficient to enhance product sustainability: key criteria influencing the total life-cycle of a product must be considered during its design process. Product and processes interact at multiple levels in a production system: it is essential to develop a model-based sustainable manufacturing methodology in view of the product life-cycle as a basis for product and process innovation in sustainable manufacturing. A useful guide for understanding the interaction between the various levels in the implementation and realization of a sustainable product is the one proposed and described Figure 10.

Figure 10 – Workflow to enhance sustainable products (Jawahir I.S. et al, 2013).

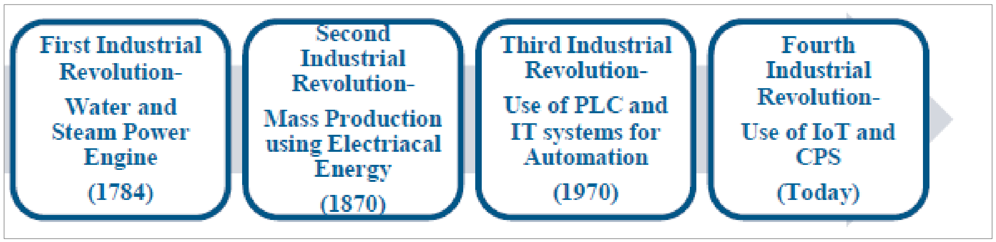


Overall, the principal sustainable industrial practices undertaken can be summarized as follows: i) *ecodesign,* which is the designing phase of a product's life cycle, ii) *Green Supply Chain (GSC)*refers to sustainable operations and practices together with suppliers' and/or customers' covering project designs, selection of raw materials, selection of suppliers, green purchasing, packaging and logistics iii) *Cleaner Production (CP):*this refers to the process efficiency (considering environmental, economic and technology scale efficiency) and iv) *Reverse Logistics (RL):* this refers to the optimization of waste.

1.5 INDUSTRY 4.0

In order to apply the concepts of the circular economy and industrial symbiosis, a new way of operating on the part of industrial systems has developed, with the aim of minimizing the logistics distances to almost zero: this system has been dubbed Redistributed Manufacturing (RDM).The key role is linked to a redistributed production activity, so RDM'saim is to minimize discarded parts through digital production technologies. Companies that operate in adjacent confined environments exploit their proximity as a more efficient synergy, while benefitting from a further resource efficiency, in the sense that the waste of a company falls into the cycle of another to be recovered (for example, a company producing components from MP sends back cut-outs to the supplier for recovery).This new manufacturing vision, developed for megatrends of mass customisation, is flexible, custom-made and included in manufacturing. Based on this, it is fundamental that this operation be accomplished with a progression and acceleration in technology. Modern technological development and communication systems must support these smart production systems and that is why we are currently witnessing and creating what has been defined as Industry 4.0. Communication systems such as *Cyber Physical System (CPS)*enable better and more efficient communication and data exchange (Figure 11).The term Industry 4.0 refers to the stage of the industrial revolution which is currently taking place. The change from the previous concept lies in the novel way of controlling an organization at all levels by a system of telematics.

Figure 11 - Four industrial revolutions.



1.6 CONCLUSION

The current environmental debate has made the world aware that it has to face the continuous depletion of resources and huge amounts of harmful emissions into the air, water and the ground. People understand that more efforts should be made to protect the environment and to stop providing for their never-ending needs which do not respect ecological limits. In fact, a revitalized global partnership is needed to support these efforts. This has been recognized, for instance, in the 2030 Agenda, which promotes a re-formulation of the habits of mankind and industries by transitioning from business-oriented to a more collaborative and cooperative value chain optimization. To reach these ends it is essential to thinks about sustainable manufacturing processes, which look at a reduction in the depletion of resources by considering an alternative, that of a “circular economy ”Thus, a future is envisioned with zero waste or a reformulation of the waste concept, in the sense that it is converted into a secondary resource. For this purpose the principles of sustainable manufacturing have been identified and formulated into the 6R concept. Companies play a key role in the realization of strategies to reduce the environmental load: action is needed at the level of product manufacturing. The next chapters will discuss business planning in order to implement sustainable manufacturing, i.e. the concept of Life Cycle Sustainability Management (LCSM).

2. AUTOMOTIVE SECTOR CHALLENGES TO ACHIEVE SUSTAINABILITY DEVELOPMENT GOALS

"We need to shift the discussion towards an integrated approach covering safety, emissions and the flow of traffic".
(Prof Ulrich Seiffert, Technical University of Braunschweig.)

"Predicting customer behaviour is pretty difficult. We therefore need to have solutions to all kind of needs. Influencing customer behaviour actively is usually not far reaching enough; results quite often differ from the intention so that overall effects do not go in the right direction even if intentions are good".
(Dr Thomas Schlick).

Magneti Marelli,as an automotive parts supplier, is responsible for their products and the effects they cause at different stages of the automobile production chain: from the manufacturing of parts, to the effect of their operation during vehicle use, and finally to the relevant influence in the EoL management options and results. The company is strongly rooted in the automotive context and operates according to the regulations and references relating to the sector. For this reason, in order to contextualize the sector of origin, the present chapter gives an overview of the main issues related to the role of the automotive sector, setting the perspective of the impact of sustainability.

Chapter 1 focuses attention on the motivators encouraging sustainability activities, in response to the alarming increase in the consumption of resourcesand to global climate change. Surveys report that the most exploited non-renewable resource is crude oil and the sector responsible for the greatest consumption of it is the transportation sector. Moreover, the worsening of urban air quality represents an additional damaging effect caused by the sector. In brief, the transportation sector accounts for the consumption of two-thirds of total crude oil and is the source of one third of all GHG emissions. Vehicles are exceedingly resource intensive products, especially considering their operation use phase (particularly for internal combustion engine vehicles), causing a considerable amount of fuel consumption and the generation of CO_2 emissions. In addition, dismissed vehicles are difficult to recover; every year in Europe, End-of-Life Vehicles (ELVs) constitute about 8-9 million tonnes of waste. The automotive industry is aware of having to take part in the environmental sustainability challenge, which considers air quality to be one of the main concerns for the industry, stakeholders and public. As a result of both economic incentives and mandatory legislative requirements, the automotive sector has embedded the circular economy as a part of its DNA. To face this dynamic set of challenges, it has started to focus attention on the implementation of sustainability programs, incorporating policy regulations from the organizational to the manufactured goods level.

Looking at the industry's global market trends, we can affirm that the automotive sector is on the rise. Compared to 2005, world car sales are expected to quadruplicate by 2050. Most of this growth is anticipated in Europe and in emerging countries such as China and India. This dramatic increase is expected to result in significant GHG emissions, besides a greater demand for fuel, a considerable exploitation of materials and a corresponding increase in the waste produced, especially at the EoL stage. At present, the European automotive industry is among the world's largest producers of vehicles. The positive effects will be an increase in the workforce and growth in investments in innovation, resulting in increased economic and social benefits. In this context, it is worthwhile considering the implications of the development of sustainability for the automotive sector. For this purpose, key factors have been pointed out and discussed, including the main aspects of issues related to the development of sustainability. Particular attention has been given to the question of GHG emissions, through the investigation and analysis of the dynamics of the problem of CO2 reduction, shedding light on the challenges and related issues and setting them in situations.

With regard to the experience of car manufacturers, the actions and the application of case studies aimed at tracing their effects on environmental impact have been presented. In all these efforts, the automotive industry has continued to stress the importance of joint actions by all the actors involved. Carmakers, their stakeholders, governments and consumers all share this common goal. To recap, the automotive efficiency-improvement drivers have been shifted to balance and improve different facets: investment in research and development activities in order to respond to consumer demand and confront tougher regulations while ensuring the sustainability of vehicle production and to deliver, in advance, improvements in the environmental impact. Thus, critical actions are necessary to foster an industrial renaissance embedded in the sustainability theory. The progress made puts the automotive industry on a good footing to meet the challenges ahead and give an orientation to environmental impact concerns while balancing social and economic welfare in dealing with the following questions:

- How do carmakers view their responsibilities with regard to the environment?
- What is the organization's response to innovative or new ideas?
- How can embedding sustainability into core business drive sustainable change?
- How can the automotive industry provide a swift response to the environmental impact?

- Where do car producers stand as regards the reduction of exhaust pipe emissions and could they be further reduced?

Finally, the research into solutions for lighter weight vehicles is really gaining momentum at a time of greater fuel economy and better performance.

2.1 FOREWARD - BACKGROUND

Surveys report that the most exploited non-renewable resource is crude oil (a share of 47%) and the most outstanding consumption is connected to the transportation sector with a share of 64%(IEA, 2017). Moreover, an additional damaging effect caused by this sector is represented by GHG emissions. In brief, the transportation sector accounts for two-thirds of total crude oil consumption and one third of GHG emissions. Vehicles are extremely resource intensive products which also cause the generation of a considerable amount of waste. Consequently, the European Directive 2000/53/EC has fixed new targets for vehicle recovery (European Commission, 2015).

With regard to the European context, emission restrictions for road vehicles have been constantly tightened over the last four decades. At present, the “Euro standards” and the regulations on carbon dioxide emissions provide a framework to set emission controls.

Overall, within European countries, environmental regulations may be summarized according to the particular issue addressed: the 2009/125/EC, is dedicated to energy-related products, ERP, the 2009/443/EC to CO2 emissions from light-duty vehicles and the 2000/53/EC to the field of end-of-life vehicles, ELVs (European Commission, 2009).

To respond to these urgent issues, car makers OEMs have started to adopt strategies to enhance sustainability purposes and CO2 target limits and could be summarized as follows: i) the improvement in the efficiency of the powertrain (downsizing) ii) the decrease in vehicle mass weight or iii) the use of an alternative engine system such as electrification and the double formula of hybrids and range extenders.

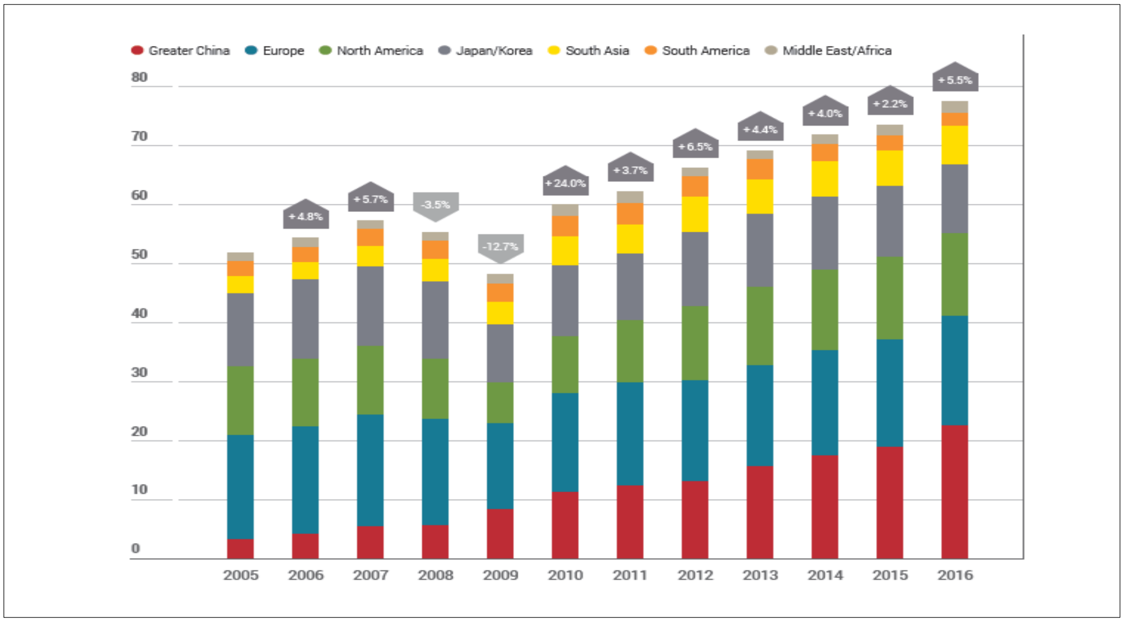
2.2 KEY MARKET INDICATORS IN THE AUTOMOTIVE INDUSTRY

Undoubtedly, our society is intensely dependent on transportation and the growth of the population and welfare will lead to a sharp increase in the demand for vehicles. Such patterns suggest an unavoidable increase in the exploitation of resources for car production and a worsening of the effects on climate. Another relevant issue will be the increase in the amount of discarded materials at the EoL stage when the car is scrapped.

As discussed in chapter 1, climate change is a common problem which affects the whole community; d its effects should be solved and/or reduced by a cooperative contribution on a worldwide scale. In this context, among other sectors, the automotive sector is playing a leading role, since it accounts for almost 16%(OICA, 2015)of man-made CO_2 emissions.

The reason behind this is twofold: among the various anthropogenic activities, the greatest amount of GHG emissions are generated during the vehicle's operation and, in addition to this, the number of vehicles in regular circulation has been increasing considerably. The number of cars sold worldwide is also steadily increasing(Statista, 2017).As a consequence of the demand for vehicles, production has been growing continually. The increase in demand can also be attributed to the diminished period of vehicle use which has passed from an average of 15 years to an average of around10.7 years(ACEA, 2017-2018).Figure 12 presents an overall picture of passenger car production worldwide (expressed in units of millions), as well as the increased percentage between the various years from 2005 to 2016. For each year, the amount has been divided according to the selected countries considering: i) Greater China ii) Europe iii) North America iv) Japan and Korea v) South Asia vi) South America and vii) Middle East and Africa. As we can see from the stacked bar chart, from 2010 onwards there has been an upward trend, with the greatest increase recorded between 2011 and 2016. During this last year the highest figures in car production were recorded. On examining in detail the production of the different regions, the following conclusions can be drawn: during the last eleven years Europe was always the largest producer, followed by North America; in recent years China has begun to take hold, to the extent that it has slightly overtaken the European production. With regard to the European territory, the highest production rate observed is that of Germany, followed by the United Kingdom, France and Italy.

Figure 12 – World passenger car production for selected countries(ISHI Markit, 2018).



All these facts are associated with positive benefits resulting in the increase of economic and social well-being as they promote employment and generate wealth. Data from statistics collected in accordance with the European scale, report that in the automotive sector 12.6 million people are employed, which means 5,7% of the population, of which 3.3 million are involved in the manufacturing application (ACEA, 2017-2018). The underlying disadvantage is that inevitably the increase in production has led to a greater consumption of resources in terms of materials and energy. However the greatest chargeable burden can undoubtedly be attributed to the release of harmful gas emissions, mostly GHG. To respond to these market forces, governments worldwide have enforced more stringent regulations on the OEMs to limit the consumption of energy resources, especially fuel and emissions. In order to address this objective, car makers are constantly being challenged to respect local regulations by adopting different criteria in the selection of their product portfolio.

"OEMs and suppliers should embrace emission regulations and technologies… and use them as competitive advantages" – Dr. (David Cole, Chairman Center for Automotive Research).

The automobile industry in the EU has made great strides in regulations aimed at reducing CO2 emissions from light duty vehicles, by imposing a reduction of at least 20% in CO2 emission levels by 2020 compared to1990 levels. The cornerstone of European regulations could be summarized as follows: "*By 2021, phased in from 2020, the fleet average to be achieved by all new cars is 95 grams of CO2 per* *kilometre. This means a fuel consumption of around 4.1 l/100 km of petrol or 3.6 l/100 km of diesel*"(European Commission, 2009).

Under increasing pressure and faced with the new European emissions targets, the automotive sector has started to become involved in sustainability programs by investing enormous financial resources (approximately €50.1 billion annually) dedicated to R&D. The ultimate goal of the automotive industry is to find a balance between technological efficiency and cost-effective sustainable solutions,thus harmonizing the performance characteristics of the products with properties of eco-compatibility. Consequently, the automotive sector has set new internal regulations, which have led to significant changes within the organizational system, resulting in a reformulation of the production system of the sector, together with the involvement of its stakeholders and its associates. The new system has turned towards a circular economy approach, in order to pursue resource efficiency in their manufacturing technology and products, while reducing the carbon footprint.

Overall, part of the solutions could be translated into a decrease in the waste of resources, by extending their service life through the re-manufacture of parts, thus guaranteeing savings in energy and resources. It has been confirmed that, in this context, the circular approach has reduced by remarkable 70%(ACEA, 2015), the total waste spawned. Nevertheless, the most urgent issue the automotive sector is facing involves the improvement of fuel efficiency and the development of an alternative power train, with a view to offsetting the most crucial factors of vehicle environmental impact linked to its usage. In fact, among other factors, vehicle usage has resulted in the production of the greatest environmental issue because of the amount of fuel required for its operation and the release of exhaust pipe emissions. With regard to the technological engine options, two aspects offer room for improvement: new engine concepts and the formulation of alternative fuels.

Generally, to decrease fuel consumption and the production of emissions, the strategies car makers have adopted are directed at: i) improvement in fuel efficiency ii) the development of an alternative vehicle powered by alternative natural or renewable bio-fuels, and possibly iii) vehicles powered by electrification technology. Undoubtedly, the refinement of the traditional internal combustion engine has played a significant part in achieving cleaner vehicles. However, as of now the extent of their role is hard to predict. Currently, the market is offering the following alternative power train propulsion systems: i) hybrids ii) full battery electrics iii) hydrogen fuel cells iv) compressed air and many other types. Although these new technologies have been properly developed, their application is still at a minimum level due to several problems, such as: i) the level of development in the technology and ii) the availability of fuel and infrastructure.

> *"Based on our current technological know-how, we expect the combustion engine to remain the dominant powertrain concept over the next decades". (Dr Klaus Draeger from BMW)*

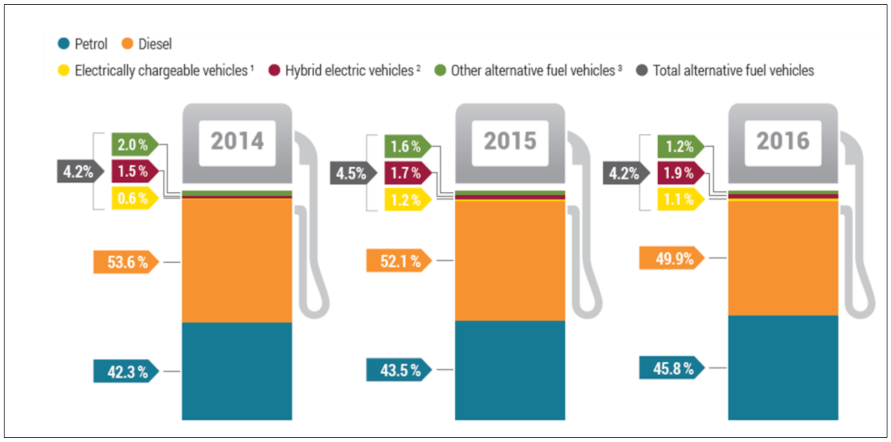
With respect to the short-term future it is expected that internal combustion engine will still maintain its dominant position over the other powertrain system options.

Currently half of new passenger cars run on diesel; the following chart highlights this fact. Figure 13 presents data on the fuel typology used in passenger cars during the last three years. The classification includes the following fuel and engine categories: i) petrol ii) diesel iii) electrically run vehicles[1] iv) hybrid electric vehicles[2] and v) others[3]. From the data reported it is clear that diesel and petrol, with a share of more than 95%, are the favourites. According to the records, from 2017 onwards a decline has been recorded in the diesel market share which has been offset by an increase in petrol vehicle sales. On the other hand, the market of electrically-chargeable vehicles (ECVs) is well above the 5% share.

In fact, petrol passenger cars have overtaken diesel and electric cars, having become the best-selling car type in the EU-15, with a market share of nearly 50%.

> *"Policy makers need to be aware that this shift to petrol engines with higher CO2 values will pose additional challenges to meeting future CO2 reduction targets". Erik Jonnaert, Secretary General of the ACEA).*

Figure 13 - New passenger cars in the EU15 by fuel type **(ACEA, 2017).**



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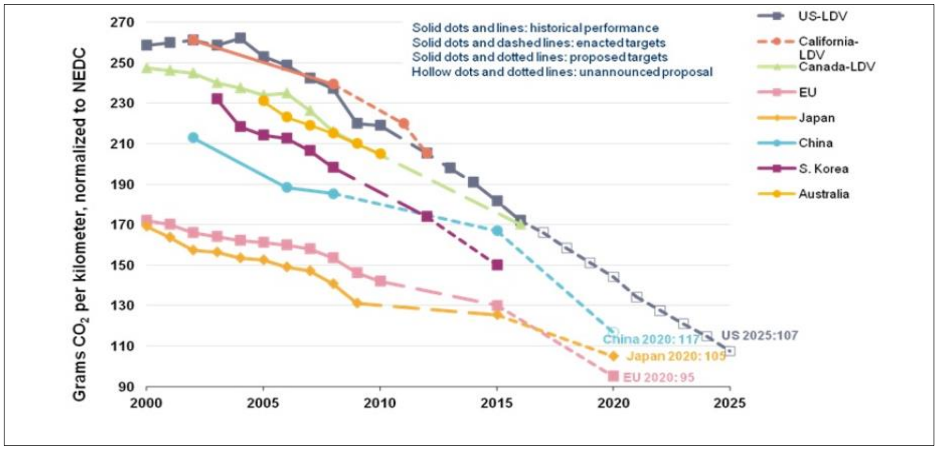
[1] Includes battery electric vehicles (BEV), extended-range electric vehicles (EREV), plug-in hybrid electric vehicles (PHEV) and fuel cell electric vehicles (FCEV).

[2] Includes full and mild hybrids.

[3] Includes natural gas vehicles (NGV), LPG-fueled vehicles and ethanol (E85) vehicles.

Besides the powertrain system, room for improvement could be obtained through the optimization of transmission efficiency, as well as the driver assistance systems, by improvements in the dynamic drag through an alternative design and by the use of lighter eco-friendly materials. Thanks to the success of the application of these strategies over the past two decades, the sector seems to have adopted the right line. Figure 14reflects the industry's efforts to reduce CO_2 emissions from production and provides evidence of the effectiveness of the drop to the recommended level. The line chart reports the emissions trends generated for the world-wide automotive industries in the selected countries for the specific time-frame. In is evident that the CO_2 emissions produced per car dropped between 2000 and 2016 (the last recorded) and it is anticipated that this downward trend will continue. In the near future, the development of new vehicles should enable a reduction of roughly 42% compared to 2005.According to the graph, emissions have been sharply reduced in the case of all the regions. The lowest level registered is for the European and Japanese markets, while the worst is observed in the US, whose performance lags behind.

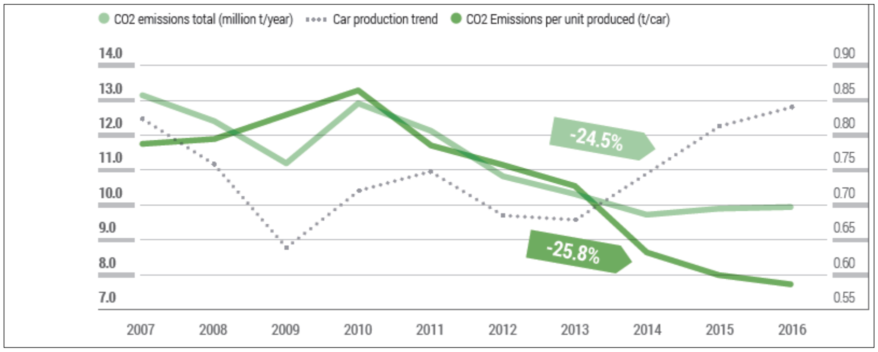
Figure 14 – CO2 emissions trend per km for the selected countries in a specific time-frame [ICCT, 2012].



Overall, the CO_2 emissions produced per car have plunged by 25.8% over the last decade. This result is clearly marked in the graph reported in Figure 15, in which the emissions produced (in tons) at the European level are reported together with the production trend (expressed in the number of cars produced), thus normalizing the emissions in relation to productivity (expressed in t/car).

As can be seen from the graph, despite the fact that car production has been growing since 2013, carmakers have been able to reduce emissions to the extent of halving them. This is the result of the huge efforts made by manufactures, who have preferred the use of renewable and/or low-carbon sources.

Figure 15 – CO$_2$ emissions and car production trend in Europe from the 2007 to the 2016.

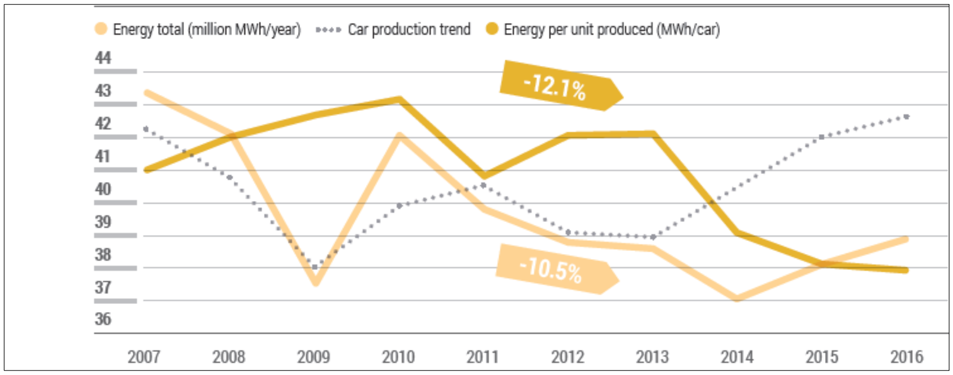


As its primary aim, the automobile industry has put forward solutions in order to achieve short-term CO$_2$ emission limits. While it has concentrated mainly on the reduction of emissions, other elements with additional environmental impact have been brought about by the automotive industry, which certainly need to be addressed. A wide array of legislative requirements has been put in place by government directives to impede the exploitation of renewable resources and promote efficiency in their management and selection. Recently, during the Frankfurt Motor show, which took place on the 13th September 2017, the European auto industry set itself a new target to further reduce CO$_2$ emissions for cars within a specific time frame (ACEA, 2017). To be precise, the plan suggested by ACEA is a 20% emissions reduction by 2030 from the 2021 level. This new target is difficult but necessary in order to be in line with the Paris global agreement and with the EU climate and Energy Framework.

> *"Our industry is committed to being part of the solution when it comes to decarbonisin groad transport, while at the same time reducing pollutant emissions". (Zetsche)*

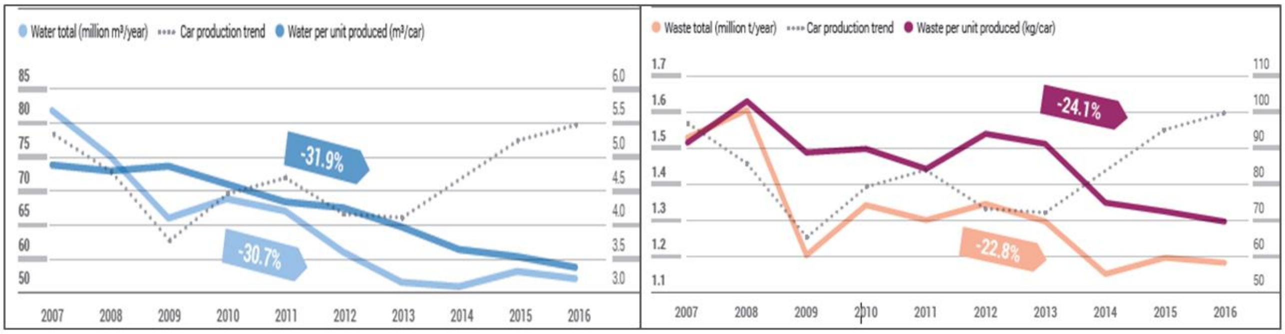
As has already been said, the environmental impact generated by the automotive sector is not exclusively limited to the fuels and emissions concerns, although these are the most incisive problems at the moment. Besides initiatives for reduction of CO$_2$ emissions, automobile manufacturers have also pointed to the consumption of materials. The strategy for reducing the environmental impact also affects the resources associated with car production, due to the increase in the number of cars. Moreover, vehicle technology has improved over time, making vehicles more intelligent, providing them with smart systems and making them safer and more efficient as a whole. The result of the improvement in vehicle technology and the increased market demand has led to an increase in the energy demand for their production. Consequently, automotive makers have started to set up greater controls to optimize the mix of energy used in their manufacturing plants, which also has repercussions on production costs, thus delivering improvements in efficiency across every aspect of their business. In the last few years vehicles have become more and moreequipped to be smarter and safer as complexity in manufacturing technology has been augmented. This increase has affected the manufacturing load management so as to balance the resources dedicated to production as well as the waste produced. In fact, more attention has been given to reducing the amount of auxiliary materials and the demand for energy as well as the waste materials and effluent. To reach manufacturing efficiency, more attention has been given to monitoring and reducing the consumption of energy, the water consumed, and the generation of wastewater and scrap. The results of these efforts have led to a sharp decline in the last five years, as illustrated in the line chart in Figure 16. At the beginning of 2007 till 2013 a fluctuating trend can be observed, with no considerable decrease. The effective improvement started in 2013, leading to a dramatic fall up to the present day. The results shown for the given period reveal an average decrease in energy per unit of car produced (expressed in MWh/car) of around 12%.

Figure 16 – Energy consumed per unit car produced in EU from 2007 to 2016 (ACEA, 2017).



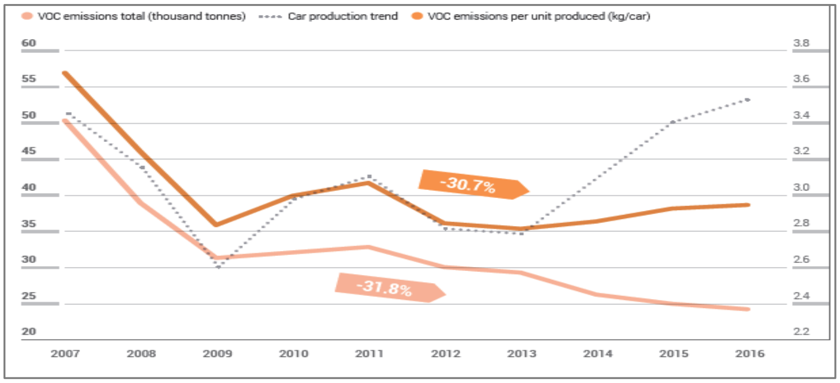
Another important element, which forms part of the manufacturing stage, is the attention paid to the water consumed. In Figure 17 are shown two trends referring to the water consumed for the production of one car unit (expressed in m^3/car) and the waste water produced during the downstream process (expressed in kg/car). From the graphs it can be seen that both trends are downward, especially the consumption of water used for the production. The reason behind this may be due to the increased application of recirculation technologies for the reuse of water. This strategy is in line with the concept of the circular economy which the automotive sector is now increasingly applying. The waste generated per unit for car-making went down by 24.1% over 10 years. To sum up, water consumption per car produced has dropped by 32% since 2007 and waste fluctuation has dropped by about 24%.

Figure 17 - Water consumed (sx) and wastewater (dx) per unit of car produced in EU from 2007 to 2016 (ACEA, 2017).



Another concern in need of monitoring is represented by volatile organic compounds (VOC). These are organic solvents generated by manufacturing activities, which are mainly emitted through painting and/or surface treatments. The graph in Figure 18 shows the amount of VOC produced per unit of car produced and is expressed in kg/car for a period starting from 2007 up to 2016. As can be seen from the chart, the quantity of VOC released dropped considerably in this period, by approximately 30%.

Figure 18 – VOC emissions per unit of car produced (kg/car) from 2007 to 2016 (ACEA, 2017).



2.3 A SUSTAINABILITY PLAN AT CORPORATE LEVEL

The automotive sector has shifted its attention to initiatives for reduction in environmental impact by the implementation of sustainability programs, incorporating policy regulations and activities, through a new operating system called *Industrial Ecology*. The purpose of this innovative system is to provide a conscious and useful procedure to help in the management and optimization of all industrial resources (materials, energy and capital) with respect to company objectives and sustainable development principles starting from the organizational level to that of the product. Although the scope of the present thesis is to focus attention on sustainability applied at product level, a description of the background instrument applied at corporate level has been given, firstly, to gain more knowledge regarding the actions being carried out by the companies to meet sustainability development targets and secondly, because such principals have inspired and steered the arguments and themes which have shifted to the product level. Normally, the structure of an organization changes as a consequence of the organization's growths that, in time, the company will develop a more consciously designed framework to accomplish the purpose of improving its sustainability performance. The challenge being faced today is that of sharing the gains by creating economic growth, environmental progress and social benefits. This novel business-thinking has promoted new management instruments aimed at gaining a Corporate Social Responsibility (CSR) award for its performance. Basically, the CSR is a volunteer instrument that deals with ethical implications generated by business activities, both internally and towards those outside by establishing a code of conduct. In order to set out inspirational principles and to manage new arrangements for corporate behaviour, a broad set of guidelines and codes of conduct has been widely provided. Such guidelines are useful since they constantly monitor company performance on various issues in order to help in identifying possible hot spots along their supply chain. Furthermore, these codes of conduct are generally made public so as to be auditable in order to gain market communication and visibility. To this end a large variety of tools are offered, though often lacking in clear and full comprehensive directions for their applications and use. This section regroups codes of conduct in order to draw a picture of the present landscape in the field of responsible management systems. Typically, the guidelines are structures which provide sets of procedures and implementation steps, proposing indicators to measure the performance. At present there is no one single guideline which can offer investigative tools dedicated to a comprehensive analysis, while integrating environmental, social and economic aspects, although an instrument like *Global Reporting Initiative* (GRI) is based on a rough summary of the three aforementioned aspects. In effect, these instruments are reinforcing each another, since they do not address the full range of CSR issues: some are intended solely as an in-depth social investigation, while others are based exclusively on environmental aspects. Turning to the practical aspect, the company needs to establish specific targets in order to monitor and measure possible improvements. In this whole context, no specific target has been imposed as a rule of thumb, but the company itself creates a skeleton of its own. The advantage that can be gained from this formula is that the use of specific customized targets reflects the company in a more representative and reliable manner. On the other hand, these tools do not allow for a comparative assessment of the performance of one company over another, since the basis for any comparison is missing and besides, there is no consistency. Moreover, the outcome of an analysis is mainly qualitative rather than quantitative.

2.3.1 RELEVANT REGULATIONS

In this section are listed in Table 1 the volunteer instruments commonly used by companies worldwide (of different sectors, including automotive ones) grouped according to particular issues. The Italian national reference instrument, which offers a framework for the management of CSR behaviour, is the Q-Res project.

Table 1 – Picture of the principal volunteer instrument related to the CSR application for industries at corporate level.

Field	Relevant initiatives	Description of purpose
Environmental management standards	EMAS[4] (Eco-management and audit scheme)	It is a voluntary scheme promoted by the European Commission for the continuous improvement of the organization's environmental performance.
	ISO 14000[5]	ISO 14000 series of standards and guidelines in the field of environmental management which seek to enable an organization to develop a structured approach in order to control the impact of its activities, products or services regarding the environment.
	ISO 50001[6] (Energy management systems - Requirements and guidelines for use)	The aim of this system is to allow the organization to pursue the continuous improvement of its energy performance, as well as the consumption and use of energy.
Social management standard	SA 8000 [7] (Social Accountability)	This standard investigates labour conditions according to the following issues: child labour, forced labour, health and safety, freedom of association and right of collective bargaining, discrimination, disciplinary measures, working hours, remuneration, and relations with suppliers.
	ILO–OSH 2001[8] (International Labour guidelines on Occupational Health and Safety management)	These are guidelines for the implementation at national and organizational levels of a national framework concerning occupational health and safety management systems.
	OHSAS 18001[9] (Occupational Health and Safety zone)	This is an international standard which provides a management system regarding workers' health and safety conditions.
	ISO 26000[10] (Corporate Social Responsibility	This standard provides a definition of social responsibility as the responsibility of an organization for the impact of its decisions and activities on society and the environment, through ethical and transparent behaviour which contributes to sustainable development, including the health and well-being of society; it takes into account the expectations / interests of the stakeholders; it is in compliance with applicable law and consistent with international behavioral standards.

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[4] http://ec.europa.eu/environment/emas/index_en.htm.
[5] https://www.iso.org/iso-14001-environmental-management.html.
[6] https://www.iso.org/iso-50001-energy-management.html.
[7] http://www.sa-intl.org/index.cfm?fuseaction=Page.ViewPage&PageID=1689.
[8] http://www.ilo.org/wcmsp5/groups/public/@ed_protect/@protrav/@safework/documents/normativeinstrument.
[9] https://www.certificationeurope.com/certification/ohsas-18001-occupational-health-and-safety-management.
[10] https://www.iso.org/iso-26000-social-responsibility.html.

Quality management standards and other frameworks	ISO 9000[11]	These are families of standards known as generic management system standards as they can be applied to any organisation, large or small, whatever its product — including services — in any sector of activity, and whether it is a business enterprise, a public administration or a government department.
	EFQM[12] (European Foundation for Quality Management)	This is a European framework for quality improvement, which seeks to improve business results while giving people a better working environment, providing customers with the best possible value and quality, and taking into account the impact on society of the organization's activities.
	AA 100[13] (Accountability)	This seeks to assist an organisation in the definition of indicators, goals and targets, the measurement of progress made towards these targets, the auditing and reporting of performance and the establishment of feedback mechanisms.
	ISO CR MSS (ISO Corporate Responsibility Management System Standards[14])	The report indicates that ISO CR MSSs could build on the intellectual and practical infrastructure of ISO 9000 and ISO 14000 and would include commitments to the concept of continual improvement, to stakeholder engagement and to transparent, accountable reporting on CSR activities.

Currently, the most widely used tool used by companies for drafting sustainability reports is the GRI; instead, the other tools are used if the company's purpose is to extend the analyses when the contents are laid down by specific regulations in order to obtain the relative certifications.

Unlike the other voluntary standards, the GRI provides a reporting framework for setting the economic, social, and environmental dimensions; moreover, the guidance has been regulated according to different sectors, with the possibility of a more tailored analysis. A pilot version was created in 2002 for the automotive sector, which has not yet been finalized. Another instrument devoted to the automotive sector is the Global Automotive Sustainability Practical Guidance[15]whose main purpose is to create a more transparent link to the various stakeholders of the supply chain and to comply with their expectations. This instrument is designed to monitor a supplier's performance, using a questionnaire (BSelf-Assessment Questionnaire on CSR/Sustainability for Automotive Sector Suppliers) and is the joint effort of the various car-makers belonging to BMW group, Ford, HONDA, Jaguar, Toyota, Nissan, Scania, FCA, Daimler, GM, Volkswagen, Land Rover and Volvo. Moreover, this questionnaire is the first example of a concrete collaboration of the car-makers to shift the sustainability concept beyond company boundaries, embracing the whole supply chain, thus with a new perspective of the life cycle approach (ACEA, 2015).

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[11] http://asq.org/learn-about-quality/iso-9000/overview/overview.html.
[12] http://www.efqm.org/the-efqm-excellence-model.
[13] https://www.accountability.org/wp-content/uploads/2016/10/AA1000APS_english.pdf.
[14] https://www.iso.org/management-system-standards-list.html.

[15] https://drivesustainability.org/practical-guidance/

A further example of the new collective collaboration of automotive actors is the Automotive Working Group[16], whose aim is to share their knowledge regarding the best practices used in the OEM concepts, with the involvement of the supply chain.

A tool designed in collaboration with the stakeholders and from their viewpoint is the analysis of materiality, which is discussed in the next paragraph.

2.3.2 MATERIALITY ASSESSMENT

The materiality assessment is an instrument used to identify the most significant topic for an organisation and its stakeholders in the field of environmental, social and governance hot-spots. This tool is a structure in the form of a matrix. It highlights and synthesizes the company's and the stakeholders' viewpoints in the field of sustainability in its various dimensions.

All of the issues identified are ranked according to a scale of importance indicated by the company and its stakeholders. The themes which emerge as most significant are those taken into account and discussed in future sustainability reporting. The instrument used to identify and scale the principal topics are mainly interviews and workshops, in which members highlight the importance of global mega trends (economic growth, climate change, social matters) and their impact on the automotive industry. Examples of the applications within the automotive industrial context include: Magneti Marelli, FCA, Toyota, Ford, BMW, Volkswagen and so on….

2.4 SUSTAINABILITY AT PRODUCT LEVEL

In the following sections a brief overview of the developments and trends in passenger vehicle design and technology are provided. To this end, an in-depth examination of publications, reports, interviews and working papers has been made.

Recent vehicles are light years away from previous ones, owing to a number of features, not only with regard to their potential performance, thanks to the great progress in technology and the field of engines, but principally because they are less damaging to the environment. The main reason behind this is the progressive usage of advanced lighter materials and the redesign of vehicle structures in order to be less cumbersome. Numerous studies and documents are associated in this field of research, which is infinitely vast and continues to grow in many directions. Among the possible strategies, by far the best avenue for improving vehicle efficiency and mitigating the environmental impact effect is the reduction of the mass. A study by Koffler C. and Rohde-Brandenburger2010, has indicated that a 100 kg decrease in the weight

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[16] http://www.w3.org/auto/wg/

of a vehicle equipped with an internal combustion engine leads to fuel consumption diminution of 0.35 l/100 km. The vehicle use phase accounts for the greatest demand of fuel and the generation of CO$_2$ emissions: approximately 60% to 90% of its total life cycle energy demand.

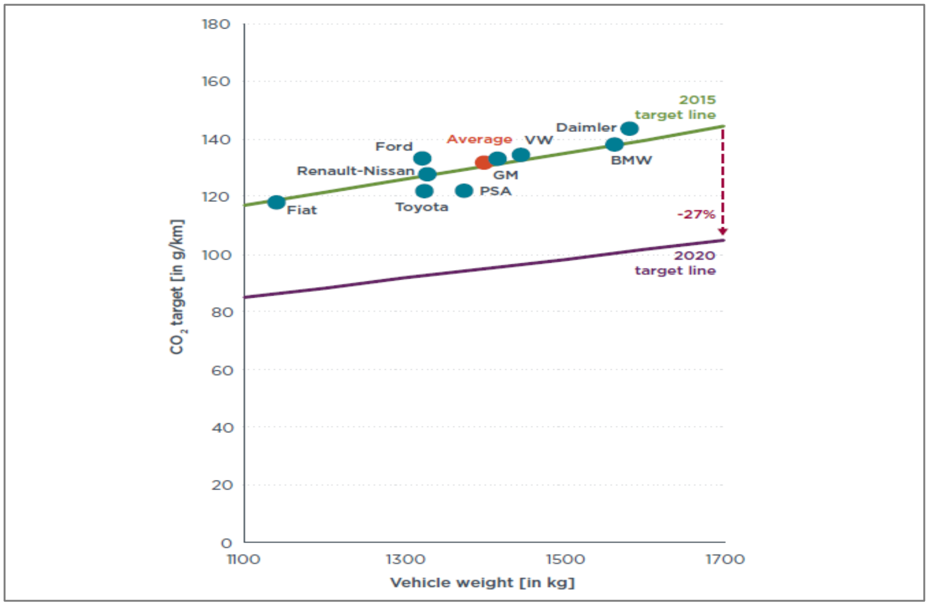
As previously discussed, the most damaging effects of vehicles occur during their use; the major effects of a lightening strategy are the diminution of exhaust pipe emissions as well as fuel consumption; in effect, there is a correlation between vehicle weight and these two factors.

In fact, European legislation (European Commission, 2015)defines a value curve that limits CO$_2$,based on the mass of a vehicle. The curve is set to attain the targets for fleet average emissions.The lightweight design, in particular, has been recognized as one of the key measures for lowering fuel usage and improving, at the same time, a car's environmental profile.

In this connection,

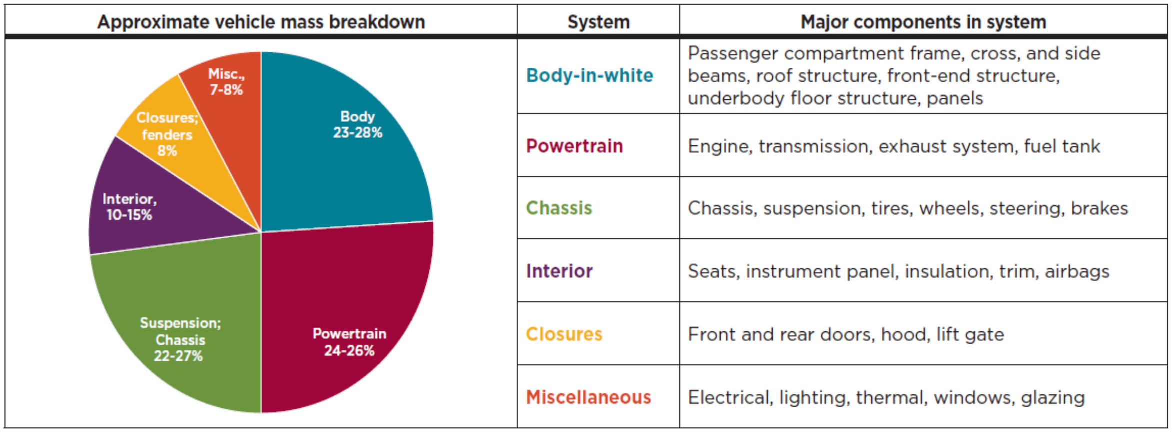
Figure 19 illustrates the average trend of CO$_2$ emissions (expressed in g/km) of European car makers, as a function of vehicle mass weight (expressed in kg). From the line chart, the mutual correlation of CO$_2$ emissions and vehicle mass is clearly evident. In particular, the present graph highlights the target slope fixed by EU regulations, set at a decrease of approximately 27% compared to 2015.

Figure 19 -Performance and target lines of key EU passenger car manufacturers from 2015 to 2020(EEA, 2013).



The overall picture of the vehicle mass distribution share is depicted in Figure 20. The division is based on the vehicle system according to the following parts: i) body-in-white ii) powertrain iii) suspension chassis iv) interior v) closures and various miscellaneous parts. In the table below are listed the major components that make up the specific system. From the pie-chart, it can be concluded that the highest mass incidence is represented by the body-in-white, followed by the powertrain and suspension chassis. A layout of this information is useful in order to understand in effect where the problems regarding vehicle mass reduction are concentrated

Figure 20 -Distribution of weight and materials in typical contemporary vehicles(U.S. EPA & NHTSA, 2012).



System	Major components in system
Body-in-white	Passenger compartment frame, cross, and side beams, roof structure, front-end structure, underbody floor structure, panels
Powertrain	Engine, transmission, exhaust system, fuel tank
Chassis	Chassis, suspension, tires, wheels, steering, brakes
Interior	Seats, instrument panel, insulation, trim, airbags
Closures	Front and rear doors, hood, lift gate
Miscellaneous	Electrical, lighting, thermal, windows, glazing

Carmakers are implementing several strategies for boosting expected legislation. In short, the decrease in weight of the vehicle mass can be achieved by a combination of: i) substitution of materials ii) different manufacturing technologies iii) vehicle body redesign and iv) vehicle downsizing.

The substitution of materials pathway involves the use of lighter and lower density materials, while the use of different manufacturing technologies could obtain significant results and reach the same goal. However, materials and technologies are two variants which are inter-dependent: the usage of certain materials conditions the adoption of a certain technology and vice versa. The first and second strategies are the most commonly used when focusing on vehicle sub-components. A different orientation is needed if the focus is not addressing the single component but the ergonomics of the whole vehicle: this is the logic applied in the last two strategies. The purpose of re-design is to optimize the size of the engine, retain the interior volume, and gauge dimensions while maintaining the same cargo space.

The last strategy is based on vehicle downsizing and takes for granted the decompounding of the mass. If a component is lightweighted at the R&D stage, then other vehicle systems can be lightweighted.

Among all the lightweighting strategies, those relating to the use of lighter materials have proven to be the most effective. For this reason, and to provide more insight into factors regarding materials and technology, the following section is dedicated to an investigation of the existing knowledge in the field of the share of materials in a midsize vehicle, with an exploration of future perspectives, placing the emphasis on the possible benefits and disadvantages of their use according to a life cycle perspective with the repercussions that this has had in the automotive sector.

2.4.1 ADVANCED MATERIALS

The necessity of finding solutions to obtain weight reduction has paved the way for research into advanced materials, which guarantee less weight for an equal functional performance. Undoubtedly, the key technological breakthrough for the discovery and employment of advanced materials has been the various computer-aided design tools. Many projects bear witness to a deep-seated determination to make use of lighter materials for automotive applications. The *Ultralight Steel Auto Body* (ULSAB) Programme promotes the use of alternative advanced steel to substantially reduce the weight of a vehicle's body structure while ensuring safety. Examples of new advanced steel are the *High-Strength Low-Alloy Steel* (HSLA) and the *High-Speed Steel* (HSS), even though both categories are commonly grouped under the HSS acronyms. Another project which fosters the use of an advanced aluminium application is the *Aluminium Intensive Vehicle* (AIV).

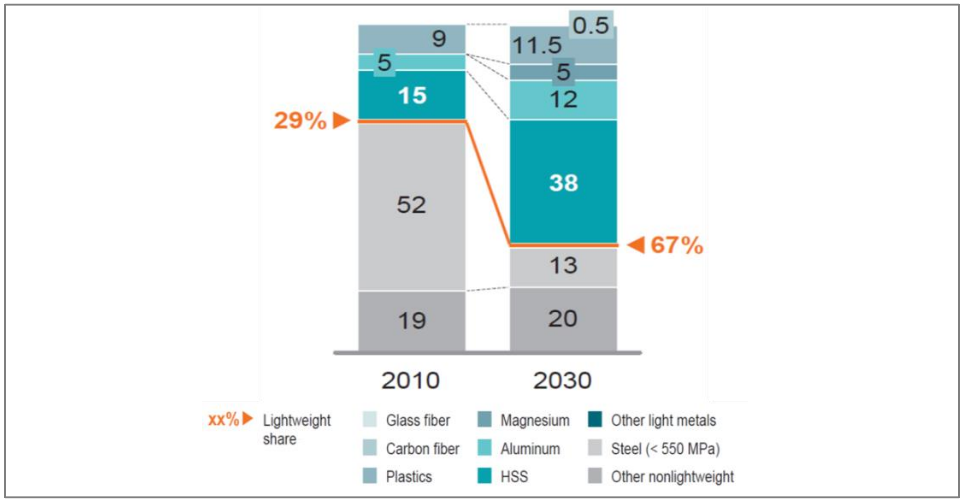
2.4.1.1 TECHNOLOGY HISTORY

Over the last two decades, the use of many innovative materials has become more and more widespread in the world of auto applications. As a result, the car's morphology has been transformed considerably. In contrast with the past, vehicles nowadays are made up of a very heterogeneous mix of materials, not only as regards the constituent matrix but, above all, the number of reinforcements in them. To highlight this point, a breakdown of the average materials used between 2010 and 2030 in the manufacture of passenger cars is provided in Figure 21. The stacked bar charts draw a picture of the present and future landscapes, showing the contribution of the individual material in the whole basket of materials employed in the automotive sector. The materials are grouped according to the following classes: i) glass fibres ii) carbon fibre iii) plastics iv) magnesium v) aluminium vi) HSS vii) steel and others (mainly other metals, glass, fluids, and interior parts for automotive). Further information observed from the graphs is the percentage of the share of lightweight materials for each of the reference years.

The most outstanding feature from the graphs is the sharp increase in the percentage of the share of lightweight materials in the middle of the two reference years.

In particular, the gradual increase of lighter materials such as HSS, aluminum, plastic and fibres was accompanied by a sharp fall in the employment of steel. Looking ahead to the medium-term, the usage of lightweighted components is expected to grow even more, at least doubling in the next 20 years.

Figure 21 – Evolution of materials' share in vehicle manufacturing from 2010 to 2030 (McKinsey & Co, 2012).



Typically, a single car consists in a large number of parts, roughly 30,000[17], which are produced with different materials through various manufacturing processes using: metals, polymers, glass, ceramics etc...The selection of the material for manufacturing purposes takes into consideration a series of elements. First of all, it is selected according to its functional properties in order to ensure the safety of the vehicle. For this reason, up to now steel has been employed to meet stiffness requirements while showing at the same time a high mass incidence. But, it is also true that each component has to respect safety requirements which are strictly dependent on their usage. These functional requirements of the products are initially agreed upon with the supplier, who asks for specific tests to be performed in order to assess the reliability of the product to be sold. With the rise of EU regulations currently in force regarding these issues, selection criteria have been adapted, including as a prerogative of the material, requirements that can mitigate the harmful effects of the products on the environment. The conflicting government regulations concerning directions for mass and weight could be solved by shifting attention to the resistance-density ratio i.e. specific stiffness [R[18]/d[19]]. In order to be attractive, the material ratio should be the highest possible (i.e. magnesium and aluminium).

Part of the answer lies in the use of advanced materials such as high strength steels (HSS), aluminum-reinforced alloys, plastics-reinforced polymers or by combining their forms so as to develop particular structures called sandwich materials, which are combinations of the three.

Normally steel and aluminium are employed for the production of structural parts to produce frames or seat structures. When a high strength is required (i.e. transmissions), the selection falls predominantly on

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[17] http://www.toyota.co.jp/en/kids/faq/d/01/04/

[18] Resistance

[19] Density

high-strength steel or carbon fibres. For the production of interior parts which generally do not require high crush and stress resistance, plastics are commonly used.

Among the wide array of vehicle components, automakers concentrate mostly on the vehicle body structure, which offers significant room for improvement. The reason for this is due to the fact that approximately 40% of vehicle mass is attributed to the body structure (Figure 20). Furthermore, it is the most critical part since stringent functional requirement targets (safety, strength, stiffness…) need to be met.

2.4.1.2 NEW FRONTIERS IN LIGHT MATERIALS FOR AUTOMOTIVE APPLICATIONS

In order to balance specific programmes of constraint and guarantee in functional performance, the steel industry is developing what are called "third generation steels" for most body structures. This innovative steel-intensive solution promises to provide high strength and safety conditions, while enhancing ductility, without compromising vehicle design. In this way vehicle architecture continues to be changed by the use of more mass-efficient steel. These patterns forecast the possibility of an additional 5% to 10% reduction in body structure mass over what agencies projected would be achievable by 2025(Gehm, 2016). The reduction in weight is obtained by the substitution of a thinner component (with a lighter material sandwiched between outer layers of steel) of advanced steel which performs with the same strength and stiffness as the previous mild-steel sheet. This is possible thanks to the advanced high-strength steel (AHSS) technology which embraces a broad spectrum of steel grades ranging from mild to press-hardened and offers a wide selection grade for the specific site within the architecture of the body structure.

It has been demonstrated that by substituting these novel steel materials it is possible to obtain reduction margins of up to 25% (World Auto Steel, 2018) over the entire mass weight of the vehicle. The AHSS embraces a wide array of alloys which are produced with a specific manufacturing technology in order to get the desired micro-structural combination of chemical compositions and multiphase microstructures. The family of advanced high-strength steels consists of: i) dual-phase (DP)ii) transformation-induced plasticity (TRIP) iii) high-strength low-alloy (HSLA) iv) complex phase (CP) v) twinning-induced plasticity (TWIP) and vi) martensitic steels.

Notwithstanding these steel properties, other materials have been found to be suitable for vehicle structure applications. Materials such as aluminium and reinforced plastics have rapidly developed over the years, improving their properties more than ever before. Industry dealing with the new materials is riding on the innovations, as growth in knowledge and higher performance is progressively increasing.

The continuous investment and interest in this category of materials is mainly due to the fact that they are far lighter than the AHSS applications, thus allowing a greater reduction to be achieved.

From the application of several case studies it has emerged that the percentage range of weight reduction achievable through the use of the lightweight materials in place of low-carbon steel for structure applications is: i) 15 ÷25% for AHSS ii) 25 ÷35% for GF-composite iii) 40 ÷50% for aluminum alloy and iv) 55 ÷60% both for magnesium and CF-composite(Taub A. and Luo A., 2015).

It is apparent from this that the concept of the uni-body steel structure is now outdated.

In addition, with a greater emphasis on decreasing the mass of the powertrain system, automakers have begun to replace standardized cast iron, which is a heavy ferrous metal, within an alternative lighter selection of materials that can retain the necessary strength to withstand the same forces. To this end, the selection has transferred to aluminum alloys and other nonferrous alloys, such as magnesium.

Aluminium applications are increasingly gaining ground in the automotive market, especially when projects such as AIV are intended to be applied. By 2020 automakers are projected to increase their use of aluminum by an estimated 32% per vehicle above the 2012 levels(Scott Unlick, 2015).

Among the possible lighter materials for automotive applications, plastics and composites present the greatest weight reduction prospects across each application segment. At present, an extensive number of opportunities are available across vehicle segments to take advantage of the use of thermoplastics as the most effective lightweight choice.

At the forefront of this landscape, new composite materials and manufacturing technology have opened the window to the possibility of achieving hitherto unreachable goals as regards lightweighting. However, further advantages could be obtained with the use of plastics.

Some authors have declared that plastics in an automotive application could save 30 times more energy over its life cycle LC; this means that up to 200 ÷ 300kg weight reduction could be achieved, which is translated roughly into 750 litres of fuel saving for 150.000 kilometers of vehicle usage. Other perceived advantages are based on the possibility of employing favorable manufacturing processes, permitting the realization of complex component structures in one production step (injection moulding), thus shortening the production time cycle. Apart from being lighter and requiring a less energy-intensive manufacturing process, plastics are noise suppressive, resistant to corrosion and more economic. In fact, the mechanical, thermal and electrical properties of plastic materials are definitely lower than those of metal; in order to achieve the same performance level, plastics often need to be strengthened by the use of additives inside the matrix. Today the challenge is to extendthe use of polymers to other vehicle compartments such as the engine. The difficulty underlying this is due to the extreme working temperatures of the powertrain component (up to 120°C) and the harsh environment (humidity, oil interface, medium cooling), besides the mechanical

performance. For this purpose, continuous fibre composite materials have increasingly become very attractive because of their excellent properties of strength and stiffness while guaranteeing lightweighting effects.
The flip side is that, when plastic materials are reinforced with synthetic filler, such as carbon fibre, they are more energy-intensive, producing and generating higher CO_2 emissions. Furthermore, plastic materials, especially when reinforced, are more difficult to be recycled at EoL than metals. The opposite effect that light-weighting has on production, EoL and use stages requires a balance of the benefits and disadvantages during the entire LC of the automotive system.
Another problem is that plastic presents a more impacting toxicity profile when compared to the same amount of other materials; this effect is due to the use of harmful chemicals for their production. Moreover the effect is worsened when such plastic is reinforced with synthetic fillers such as: glass fibres, carbon fibres, talcum powder, calcium carbonate and so on. Another disadvantage of plastic composites is that they are difficult to re-use at the component's end of life stage of scrapping since itis difficult and extremely energy-intensive to separate the matrix from the filler, so that the component is generally incinerated to recover energy. Here the efficiency of the process is strictly dependent on the calorific value of the materials; indeed some reinforcements, especially the synthetic ones, lower the amount of recoverable energy as well as slightly increasing the amount of CO_2 emissions generated at this stage. Looking at embodied energies of common composite constituents, carbon fibres present the highest value range (183 ÷ 286 MJ/kg), while glass fibres the lowest (13 ÷ 32 MJ/kg).

To counterbalance the toxicity effects of the synthetic fillers, greater focus on the use of bio-based plastics has been promoted for automotive applications. These materials present a more-sustainable alternative to conventional synthetics. During the last few years several bio-based materials and products have been introduced into the automotive industry. Bio-based materials are produced from biological fibres (grass, corn straws, flax, hemp, kenaf…) whose function is to strengthen the mechanical properties of plastics. These composites compare positively with the performance of the common composites used in the market:their fracture is non-brittle, and they enhance favourable manufacturing conditions since they are suited for an injection moulding process and require less energy consumption and fewer auxiliary materials.

In recent years, other factors have come into play when choosing a specific material for the production of a component. Apart from the compliance to functional requirements and the attempt to produce lightweighting, a retrospective analysis of the behavior of the materials at the end of life is becoming necessary. This is mainly due to the increasingly stringent regulations regarding the cars' withdrawal from use in EU countries.

Legislation on disposal to landfill, such as the Waste Landfill Directive (1999), combined with specific legislation for industry which affects composites such as the End of Life Vehicle Directive (2000) and the Directive on Waste Electrical and Electronic Equipment (2002) have highlighted the need to develop resource efficient recycling technologies for composite materials(Song Y.S. et al, 2009).

These directives enforce a fixed utilization rate of cars withdrawn from use, setting a target of 95% recyclability per vehicle per year.

Additionally, in order to reap the full benefits of recycling in terms of the avoidance of primary (virgin) material production, it is desirable that the quality of the recycled scrap be kept as close as possible to that demanded by the original application. ELV treatment involves two main steps: firstly, the draining of the entire vehicle to eliminate dangerous substances and parts (fluids, battery, tyres) and the disassembly ofa few parts for the second hand market. In a second step, the drained vehicle is reduced to the form of a wreck and inserted into a line to separate the materials according to metal, non-metal and plastic criteria.

However, the market oriented approach seems deficient for steering the choice of design in favour of materials and parts which can be recycled at the ELV stage. An indicator through which the efficiency of the recovery of materials is measured is the recyclability and recoverability rate, which is defined by the norm ISO 22628(22628:2002, 2002), the normative fixes the method for calculating the recovery of materials based on their attitude. Further information regarding the ELV management is discussed in Chapter 5. There is certainly an enormous amount of work involved but good support could be given by the right use of the International Material Data System (IMDS) or International Dismantling Information System (IDIS) to map the entire breakdown of materials..

2.4.1.2 INITIATIVES OF AUTOMAKERS TO BOOST VEHICLE LIGHTWEIGHTING

The present paragraph focuses attention on possible solutions to target lightweighting goals. These achievements could be obtained by the use of a double strategy, that of advance materials and technology. In the following section are listed a few insights drawn from academic literature, supplemented by reports on the application of case studies regarding the implementation of the concept of lightweighting in passenger cars. The use of this type of application dates back to the early 2000s.

Some formulae in this regard involve the use of innovative materials to be applied to the body-in-white structure. Since this is one of the heaviest parts of the vehicle, the adoption of lighter materials certainly offers very significant results in the reduction of the vehicle's mass weight. The challenge represented by the application of this concept is due to the need to respect functional requirements guaranteed only by certain materials. The use of innovative and high performance materials has definitely offered the possibility of reaching this purpose. Overall, the strategic line for the body-in-white structure is based on the application of the following advanced materials: i) steel ii) aluminium and iii) polymer/composite. These strategic approaches have allowed for a distinct weight-saving, occurring mainly through the use of plastic materials. The innovative concept has been formulated and applied to different car sizes: i) compact ii) midsize iii) crossover utility (CUV) and iv) sport utility (SUV). The application of such materials in the various concepts has resulted in important weight savings, from 7% to the 52%.

The following few examples regarding the application of advanced steel and their relative designations are offered: i) USLAB-AVC (ULSAB, 2002), NewSteelBody (ThyssenKrupp Stahl AG, 2003), Arcelor Body Concept(Arcelor Auto, 2004), Future Vehicle Steel(WorldAuto Steel, 2009), Lotus Study(The Intrnational Council on Clean Transportation, 2010). Other cases refer to the application of an advanced aluminium-alloy: Ford P2000(Cornille H. et al, 1998), fka Aluminium-intensive vehicle(Wohlecker R. and Wynands D., 2002),SuperLight-CAR(Volkswagen AG, 2009). These final examples look to the use of a high-performance composite: Chrysler ESX2 (Dhingre et al., 2000) and Hypercar Revolution. (Cramer D. and Taggart D., 2002).

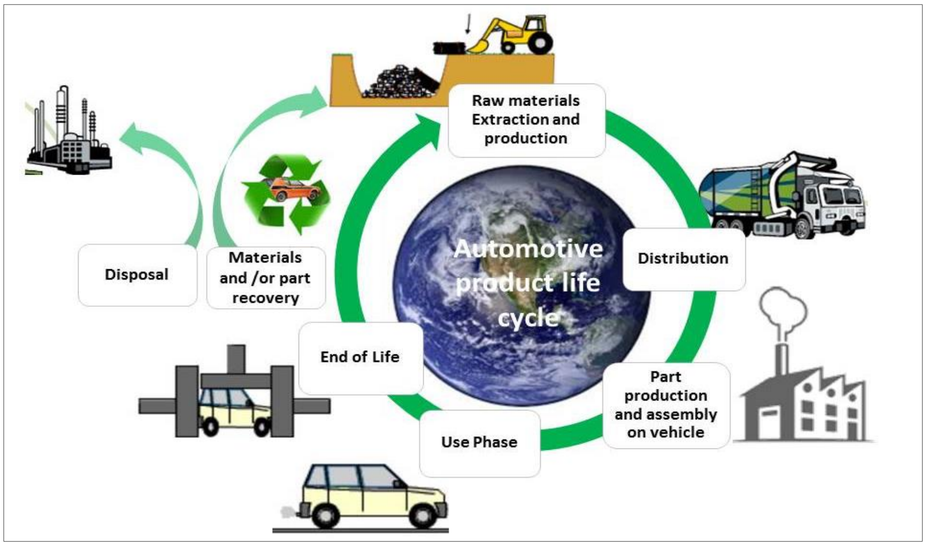
2.4.2 LIFE CYCLE PERSPECTIVE

To arrive at an efficient system which can be sustainable, it is important to try and transcend the individual system boundary and widen the perimeter so as to reach the broader aim in view, that of the application of the principles of the circular economy. In light of these issues and in order to provide a useful and objective environmental balance in the application of specific materials for the production of the vehicle and/or of the component, the best approach is to consider the whole from a life cycle perspective.

In the life cycle of the component are included all the elements related to it, from its “cradle” to the “grave”. For the component, the “cradle” means the extraction of the raw materials involved for its production and the “grave” is the ultimate phase of its scrapping. During the entire life cycle of the component, several stages can be distinguished, according to specific criteria.

For the specific case linked to a vehicle and/or component, the life cycle consists of distinct phases that can be represented in the illustration (Figure 22). In general, the life cycle of an automotive component is made up of the following splitting phases: the acquisition of resources, production, use, end of life and logistics in between the different phases. This subdivision is useful for understanding where the greatest impact generated by the component lies, and therefore where to focus attention in order to reduce the element creating the greatest impact. In addition, some phases are governable and are directly dependent on a specific actor in the supply-chain, for example, carmakers are directly responsible for the manufacturing phase; this distinction is useful for understanding who is actually responsible for a specific issue. Even though the life cycle phases may seem apparently disjointed, there are elements connecting them. In the following chapters we will see that, for example, the choice of material plays a central role in this argument. Beyond this, it is possible that solutions aimed at the improvement of one aspect of the life cycle may have negative consequences on other aspects of the life cycle; for example, plastics optimize the environmental effects in the use phase of the vehicle, but sometimes they worsen other aspects like the end of life. For the reason advanced above, an approach based on a broader perspective is certainly more reliable and representative of reality.

Figure 22 - Life cycle of a vehicle and/or vehicle's component.



The need to provide a wider overview of the effect on the environment along the whole supply chain has given rise to instruments directed at the quantification and accountability of the effects of the product on the environment, thus providing more comprehensive and efficient outcomes. Today, the analytical tool, which can provide a quantitative description of the vehicle environmental impact along the full life cycle, is the Life Cycle Assessment (LCA).

The LCA provides a systematic technique and metrics established for the analysis of the environmental sustainability performance of a product. The most commonly used technique in eco-design methodologies to assess the environmental impact is Life Cycle Analysis (LCA). LCA is a validation technique used to assess the environmental impact of a product and identify environmental burdens that arise throughout a product's life cycle from the extraction of raw materials to the end of life phase. LCA is a widely used tool, within a DFE methodology, for measuring the environmental impact of a product design. The LCA applied to the examination of vehicle impacts implies a perimeter that is extended from the extraction of the raw materials to produce each parts, to the final EoL. LCA provides useful outcomes, which address the most important environmental issues, and for these reason designers should consider this information in the selection of the best environmental impact diminution strategy. In this sense the LCA is a useful tool which can drive DfE selections and suggestions.

2.4.3. EMBEDDING SUSTAINABILITY PRINCIPLES WITHIN THE PRODUCT

With respect to the product sphere, the integration of environmental aspects has become necessary, giving attention to the entire life cycle of the product.

Starting from the principles of Industrial Ecology and the need to optimize the environmental impact of products in their whole life-cycle, the concept of *Life Cycle Engineering* (LCE) was born. In fact, LCE covers all aspects of a product's life cycle in the selection of the product design concept: starting from the choice of materials for the production of a component to the management of its end of life (or scrapping).

A suggested definition for LCE is: *"Engineering activities which include the application of technological and scientific principles to manufacturing products with the goal of protecting the environment, conserving resources, encouraging economic progress, keeping in mind social concerns and the need for sustainability, while optimizing the product life cycle and minimizing pollution and waste"*(Jeswiet J. and Szekeres A., 2014).

This new model has had a significant influence in the Research and Development (R&D) stage of a product. The innovation consists in a new approach to product design, which considers the entire life cycle of the product, thus proposing a new way of operating in the selection of eco-design choices which aims at preventing the environmental impact caused by the choice of a possible design solution for the whole life cycle. For instance, in order to reduce the exploitation of non-renewable resources, the LCE promotes the use of recycled materials, lower energy intensive production processes and the greatest possible reduction of scrap to be sent to the landfill.

The result of this new way of thinking has led to the implementation of the so-called *"Design for X"* (DfX) approach, as an innovative system which helps the R&D team to shift attention to a specific issue in the selection of possible improvements in product design. The innovation of DfX consists in the formulation of a new approach to product design which considers its entire life cycle, thus proposing a new way of operating in the selection of a product design objective. In fact "X" represents the property of the product in relation to one or more life cycle stages of the product itself. Overall, DfXhas been classified as a method that focuses attention on certain life cycle stages of a product.

Moving to environmental concerns, the *Design for Environment* (DfE) as an integral part of the DfX methodology, has emerged with the aim of integrating green principles to be applied during product design while taking into consideration the perspective of a product's life cycle, thus aiming at generating better solutions concerned with a specific subject according to its quality and functional requirements.

DfE has been defined as *"a process, integrated within design and development that aims to reduce environmental impact and to continually improve the environmental performance of products, throughout their life cycle"*(ISO 14006:2011, 2011).

The overall characteristics of the DfE approach are: the point of application at an early R&D stage, the perspective of a product's entire life-cycle and final decision-making which takes into account a specific objective using a set of values consistent with industrial ecology. DfE begins with an understanding of a product's life cycle, enabling it to be separated into many steps including: manufacturing, consumer use and the end-of-life of the product.

2.4.3.1 DESIGN FOR THE ENVIRONMENT IN THE AUTOMOTIVE SECTOR

Design for environment (DfE) applications emerge as a consequence of environmental concern strategies. These applications are mainly focused on the selection of materials and component design of materials that are environmentally friendly and recyclable.

This implies the need for automakers to integrate Design for Environment (DfE) principles beginning at the design phase, aiming at the improvement of the eco-profile of the vehicles during their use and taking care to prevent the transfer of the environmental impact from one stage to another of the life cycle.

Maximizing weight reduction (i.e., minimizing vehicle weight) requires a systems-engineering design and a combination and optimization of a series of factors: properties of materials, component functionality and costs are some examples.

One suggested DfE approach is to categorize the product in line with each of its life cycle stages as follows: i) *Design to minimize material usage* ii) *Design for manufacturing*, iii) *Design for energy efficiency* iv) *Design for end of life*.

The selection of materials plays a key-role in the application of sustainability principles during product design, since it affects all stages of a product's life cycle in terms of: material depletion, component manufacturing, mass weight of the vehicle and the possibility of recycling or re-using the component at the end of its life cycle. The minimization of the consumption of raw materials is usually obtained through the implementation of lightweighting strategies or the use of recycled materials and/or vehicle layout optimization.

Design for Manufacturing (DfM) encourages decrease in component parts and energy expenditure for the production, but also minimizing the complexity of manufacturing operations and shortening the product development cycle. A derivative of the DfM is the *Design for Assembly* (DfA), which promotes the reduction of the number of parts through the elimination of adjustments.

Design for energy efficiency concentrates on efforts to improve the environmental performance of vehicles though the development of lighter vehicles or by implementing innovative engine technologies to ensure powertrain efficiency. The lighter the vehicle is, the less fuel consumption is needed and the less CO_2 emissions are emitted. Opportunities for mass reduction include lightweighting strategies; the solutions for the reduction of the mass may depend on whether the component designs such limitation. When strength is the design requirement, heavy-steel parts can be substituted with thinner components of high strength steel, reducing the mass while maintaining strength. In order to comply with ELV directives, car manufacturers are applyinga vehicle end-of-life management tool in order to reduce the generation of waste. The study of the end of life focuses attention on the possibility of recovering materials, hence preventing waste, reducing the use of virgin resources and limiting the amount of waste generated by the treatment process. Normally, the possible options that can be classified under the umbrella of design for end-of-life can be broken down into the following sub-categories of application: i) design for disassembly ii) design for remanufacturing and iii) design for recycling. The main objective of the *Design for disassembly* is to disassemble the part with the minimum effort, in order to more easily separate the flow of materials. In fact, the disassembly strategy allows for a better recovery of a large portion of materials and parts. As an alternative, the aim of the *Design for Remanufacturing* is to return vehicle parts to an acceptable level of performance so as to allow for the re-use of the component and/or to recover materials in the state of their highest value. A possible solution to prevent discarding a part is to improve the component quality control in order to extend its lifetime and use. The third approach is the *design for recycling*, which focuses on the possibility of recovering materials from returned products. The use of recycled material entails benefits in the reduction of energy consumption for the production of virgin raw material and in the generation of waste and air and water pollution. Indeed, the composition of materials plays an important role in the recyclability process: a preferable solution is to avoid plastics, especially composite ones, and prefer select material that could be contained in a closed-loop. Plastic cannot be recovered at the same quality level as the original. Steel can be remanufactured in a quasi-closed loop scheme while aluminum can be recycled in a fully closed loop system (Mayyas A. et al., 2012).The DfE approach begins with an understanding of the product's life cycle and so, in order to quantify the environmental impact of a product, it is used in combination with LCA methodology.

The LCA is without doubt the most validated technique for assessing the environmental impact of a product and for identifying environmental burdens arising across the life cycle of the product (ISO 14040, 2006). Some authors have used the LCA framework to identify the environmental dimensions associated with each life cycle stage of vehicles. The LCA has been used to provide a useful set of environmental indicators to start the DfE process or, at the early decision stage, in order to make a pre-selection of the most favorable scenario. The risk associated with the use of LCA as an environmental selector to drive the DfE choice is due to the difficulties that could emerge with the interpretation of LCA results, since the environmental problems are addressed in the form of indicators which are detached from the designer'sunderstanding (i.e. Abiotic Depletion and so forth…). Besides, in most cases the LCA analysis has been applied with a number of assumptions, which may not lead to reliable results. For the reasons advanced above, the LCA should be carried out after the realization of a prototype and the description of the effective life cycle of the product so as to map all the effective mass and energy flows which cannot be calculated with certainty in advance.

2.5 CONCLUSION

The next few years may bring extensive developments in the automotive industry: a longer-term strategy which considers innovation and economic growth without compromising the environment.

The material selection plays a key-role since it directly affects the environmental performance of a product in terms of the properties, manufacturing and weight of the materials. To provide sustainable mobility for a growing population, innovation should match legislative limitations to preserve the environment.

The principle strategy selected by car-makers is lightweighting since it reduces the two principal problems caused by the automotive sector: fuel consumption and GHG emissions. Part of the answer lies in the employment of lighter material and component layout optimization and resizing, therefore applying DfE principles during product R&D. A new effort for lightweighting cast components of vehicles, through part redesign, advanced processes and the introduction of new materials, has yielded new lightweighting solutions and offers significant weight reduction opportunities.

Many advances in lightweighting have surpassed agency predictions in 2012. Stronger and lighter materials are available at lower costs than assumed. Advances in modeling/simulation tools and joining techniques have opened the floodgates to unprecedented levels of material/design optimization.

Even more improvements in both materials and design are on the way.

Suppliers are rapidly developing the advanced materials and methods for major lightweighting endeavors, as well as the computational tools for simulating full vehicles all the way down to nanoscopic material behavior. These tools and techniques build upon an already highly sophisticated arsenal that manufacturers are using today to make vehicles stronger and lighter than anticipated in the regulations. Many recent vehicle redesigns have reduced weight by at least 4%, already meeting or exceeding 2021 projections in the regulations. There are numerous improvements in the development of materials that were not considered in the regulations, such as higher strength aluminum, a new generation of UHSS cast components, and metal/plastic hybrid components. When the multiple other benefits of reducing weight are considered (ride, handling, braking, performance, load capacity), it is clear that the implementation of lightweight materials and better design will be limited only by the speed at which computational tools improve and better materials can be brought to the market.

Thus, the primary question is, how fast can tools and materials improve and better designs be incorporated into vehicles? The current generation of vehicle redesigns are routinely achieving about 5% weight reduction on average (some are much higher). There are two redesign cycles before 2025 and, given the accelerating pace of computational tool development and improved materials, it is reasonable to assume that each of these redesign cycles should achieve at least a 5% weight reduction. Overall, about a 15% weight reduction should be feasible by 2025 at the cost of about a third of those estimated in the 2017–2025 regulations.

3. BROADENING THE SCOPE OF LCA: TOWARDS THE LIFE CYCLE SUSTAINABILITY ASSESSMENT (LCSA) APPROACH

> *"Sustainable development is the pathway to the future we want for all. It offers a framework to generate economic growth, achieve social justice, exercise environmental stewardship and strengthen governance."(Ban Ki-moon)*

The growing importance of environmental sustainability in the corporate sector has resulted in an increase in the number of actions to reduce its environmental impact and to develop various initiatives. In the previous chapter we saw how these actions have been embodied through the use of economic tools, along with others such as energy, social and environmental balancing at the corporate level. Very often, business decisions are driven by financial parameters but with the improvement of sustainability this has become a business goal. The evaluation of criteria from environmental and social spheres is also important; however, performing this assessment in a practical and systematic way is a challenge, especially if this assessment must be scaled from a global (corporate) level to a more detailed (product) level.

To this end the growth of the life cycle approach to address sustainability problems should be seen in a wider and more comprehensive perspective.

The life cycle approach is in fact strongly rooted in the concept of sustainability because of the thinking behind it, in the sense that the analysis of this system is not defined by its distinct phases but by interactions and linkages between the elements composing the entire system and by an interdisciplinary approach, as evidenced in the impact assessment phase. Sustainability, as a concept, is defined at the macro-level. The following chapter is based on well-known dissertations and applied methodologies, used to assess sustainability at product level.

The term *LCSA* was coined as the result of an ever-increasing awareness of the importance of life cycle thinking as a way of tackling sustainability challenges, in which *LC* stands for *Life Cycle*, *S* for *Sustainability* and *A* for either *Assessment* or *Analysis*.

As a result, the scientific community has begun to seek ways to provide prompt solutions to *Life Cycle* sustainability responses through the development of standards and models. The first study, which attempted to assess the life cycle impact of a product on the environment, occurred during the1960s.

To implement an integrated sustainability policy, the environmental, economic and social dimensions have to be included in order to make equal trade-offs throughout the product's life cycle. The widespread instrument of investigation for assessing the environmental impact of a product is the Life Cycle Assessment (LCA). Instead, to measure the economic impact, the Life Cycle Costing (LCC) method has been proposed. Lastly, the Social Life Cycle Assessment (S-LCA) is at present the only social assessment method that takes into account the social aspects of a product from a life cycle perspective. All of these methodologies will be discussed in depth in the following paragraphs. Important contributions setting out the rules for assessing the sustainability performance of the life cycle of a product have been provided by the following international initiatives: the European Commission has recently published the "Product Environmental Footprint" as a contribution towards the harmonization of tools used to measure the environmental impact of products; the United Nations Environment Programme (UNEP)/Society of Environmental Toxicology and Chemistry (SETAC) have published guidelines on social assessment topics and also promote a "Code of Practice" for economic investigation and lastly, the "LCSA" includes a full framework for the three spheres of sustainability (environmental, social and economic).

Hence, in the following chapter there is an attempt to provide answers and discuss the topic of sustainability assessment from the three disjointed perspectives, along the following lines: firstly the purpose of each methodology is presented as well as that of the methodology on which they are based; secondly a more practical view is given through the presentation of case studies and examples of their applications; lastly, future directions are considered, i.e. how to further develop the methodologies, especially the LCSA and which research strategies and lines are considered relevant.

An interesting question arises as to what the actual practice of LCSA is, in particular with respect to the following aspects:

- Which definition(s) is (are) being adopted?
- What challenges to the methodology implementation are being tackled?

3.1 FOREWARD: LIFE CYCLE SUSTAINABILITY ASSESSMENT

The topic of the *Life Cycle Sustainability Assessment,* LCSA has been launched recently, as an idea for combining the three techniques, in order to assess the impact of a product in the environmental, economic and social spheres. At present, a standardized definition of the LCSA concept does not exist.

Until now, various authors have attempted to give their own definitions of LCSA in their dissertations and through the applications of case studies, albeit with fragmented and descriptive applications that are not fully comprehensive of the intended scope of the LCSA.

Currently, several definitions of LCSA do exist in literature, among which, the one proposed below seems to be the most complete.The idea of combining three LCA techniques into an LCSA was first formulated by Klöpffer (KlöpfferW., 2008), followed by Finkbeiner et al. (Finkbeiner M. et al, 2010) and is expressed in the following way:
(1) LCSA = (environmental) LCA + LCC + S-LCA.

In this way, the author explains the concept of the triple bottom line and the view of the holistic model associated with it, focusing attention on the three distinct parts of which LCSA should be composed: i) environmental ii) economic and iii) social, with their respective instruments of investigation.

However, the LCSA abbreviation is also used to indicate another framework, proposed by Guinée et al. (Guinée J.B. et al., 2011), which states that LCSA is a: "trans-disciplinary framework for integration of models". In fact, these authors have enlarged on the previous author (Klöpffer W., 2008)by proposing the concept of the integration of three distinct methodologies. In addition, they emphasize the fact that the purpose of the LCSA is more extensive than the single sum of the three methodologies (LCA, LCC and S-LCA), since: *"[it] broadens the object (or level) of analysis from predominantly product-related questions (product level) to questions related to sector…"* and *"it deepens current LCA to also include other than just technological relations, e.g. physical relations (including limitations in available resources and land), economic and behavioural relations…"*(Guinée J.B., 2016).
Based on the definitions proposed by Klöpffer and Guinée, we can thus distinguish between three dimensions along which LCSA has expanded when compared to (environmental) LCA:
The broadening of impacts: LCSA = LCA + LCC + SLCA.
Life Cycle Sustainability Assessment (LCSA)(UNEP/SETAC, 2011)plays a key-role towards the transition to Sustainable Production and Consumption patterns (SPC) (UNEP/SETAC, 2009).According to the aforementioned definitions, the techniques for the three dimensions of sustainability have to be combined so as to make the move towards an overarching LCSA possible.

Therefore, taking as a reference the sustainable development definition, a figurative presentation of the LCSA as proposed by (Schau E.M., 2012) has been drawn in Figure 23

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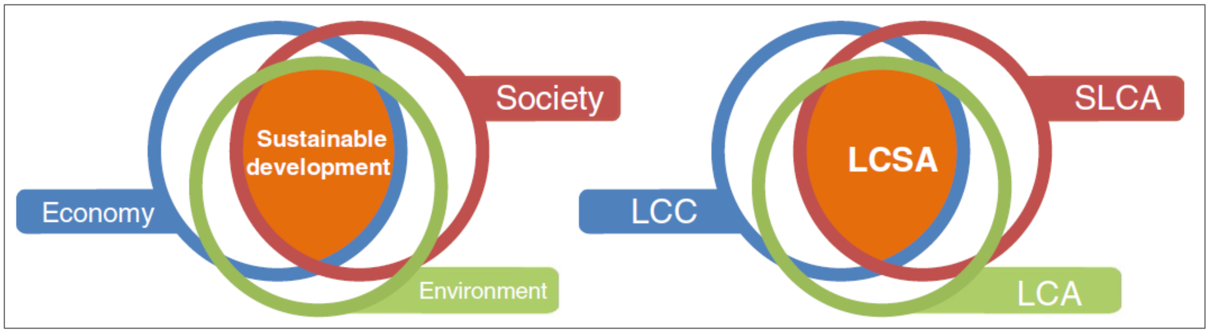
Figure 23 -Dimension of sustainability life cycle assessment (sx) and dimension of life cycle sustainability assessment (dx) (Schau E.M. et al, 2012).



Unlike the concept of sustainability development, the methodologies used to assess environmental, economic and social impact have not been developed at the same rate. In fact, a consolidated life cycle based model is necessary to implement a harmonized a full SLCA.

3.2 LCA METHODOLOGY

The concept of *Life Cycle Assessment (LCA)* methodology was born at the beginning of the 1960s following the publication of several reports on the theme of energy consumption linked to industrial activities at atime when European and North American industries had begun to pay particular attention to the saving of resources (energy and materials) and the reduction of emissions into the environment. The first company to initiate a study using the LCA methodology was Coca-Cola in 1969. The purpose of the work was to identify the beverage container that required the minimum use of raw materials, energy and emissions related to its production. This pilot project inspired a subsequent analysis to broaden the system's boundary beyond the perimeters of the industry, by following the production chain from the extraction of raw materials up to the disposal stage. The oversight of the advancement of LCA was undertaken, in 1979, by SETAC (Society for Environmental Toxicology and Chemistry), a multidisciplinary organization of professionals and representatives from industry, including public and scientific delegates.

The LCA definition provided by SETAC(SETAC, 1993)states as follows:

"Life Cycle Assessment is a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and materials used and released to the environment; and to identify and evaluate opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing, extracting and processing

raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling, and final disposal".

The first methodology proposed was rather inconsistent due to the lack of a proper data system and of a solid framework. The need for standardization soon became necessary. For this purpose, in June 1993, the International Organization for Standardization (ISO) appointed 207 persons to a technical committee with the aim of developing international rules and regulations for environmental management, dedicated to the standardization of the LCA. The first ISO standards were published in 1997 and were later updated to the final ones proposed in 2006. At present, the reference standards for the LCA are the ISO 14040 "Environmental Management Life Cycle Assessment Requirements and Guidelines".

In that period there was a remarkable increase in the amount of scientific papers and coordination activities worldwide related to the application of the LCA methodologies and, in time, it resulted in the methodology being included as part of industries' reports and documents concerning environmental activities.

3.2.1 GENERAL DESCRIPTION

LCA is the most comprehensive method to assess the environmental impacts of a product over its life cycle stages by accounting for all the relevant input and output flows during each life cycle stage, from the extraction of raw materials for the manufacturing process to the end of life, together with the transportation phases in between. As drawn in the ISO 14040 series, an environmental LCA study has four major components: i) definitions of goal and scope(ISO 14041:1998) ii) life cycle inventory (LCI) (ISO 14041: 1998) iii) life cycle impact assessment (LCIA) (ISO 14042: 2000) and iv) interpretation of results (ISO 14043: 2000).

The ISO standards provide a framework in order to give the right directions for the study so as to make the analysis consistent, reliable, applicable and comparable. However, the goal is intrinsically dependent on the scope of the owner and is defined during the definitions of the goal and scope.A definition of LCA is found in ISO 14040, where it is given as follows: "The compilation and evaluation throughout the life cycle, of incoming and outgoing flows, as well as potential environmental impacts, of a product system".

3.2.1.1 APPLICATIONS AND PURPOSE

There are several reasons why the LCA analysis is carried out in industrial settings:

- to compare alternative solutions for products and/or services while performing the same functions (mainly during the product development process);
- to identify where the dominant environmental impact is generated among the product life cycle stages;
- to monitor the main consumption streams within a company's manufacturing perimeter;

- to evaluate the behaviour of a supplier as regards environmental impact and management of resources;
- to improve manufacturing performance in terms of resources, cost savings and reduction of waste;
- to give visibility to the outside on the environmental impacts related to the product life cycle (EPD, marketing…).

3.2.1.2 REFERENCE STANDARDS

The life cycle analysis is codified by the following technical regulations:

- ISO 14040: 2006 – Principles and Framework;
- ISO 14044: 2006 – Requirements and Guidelines;
- ISO/TR 14047:2012 – Illustrative examples on how to apply ISO 14044 to impact assessment situations;
- ISO 14048: 2002 – Data documentation format;
- ISO 14049: 2012 – Illustrative examples on how to apply ISO 14044 to the definition of goal and scope and inventory analysis.

The fundamental principles, indicated in the standards of the UNI EN ISO 14040 series, for a life cycle assessment study are:

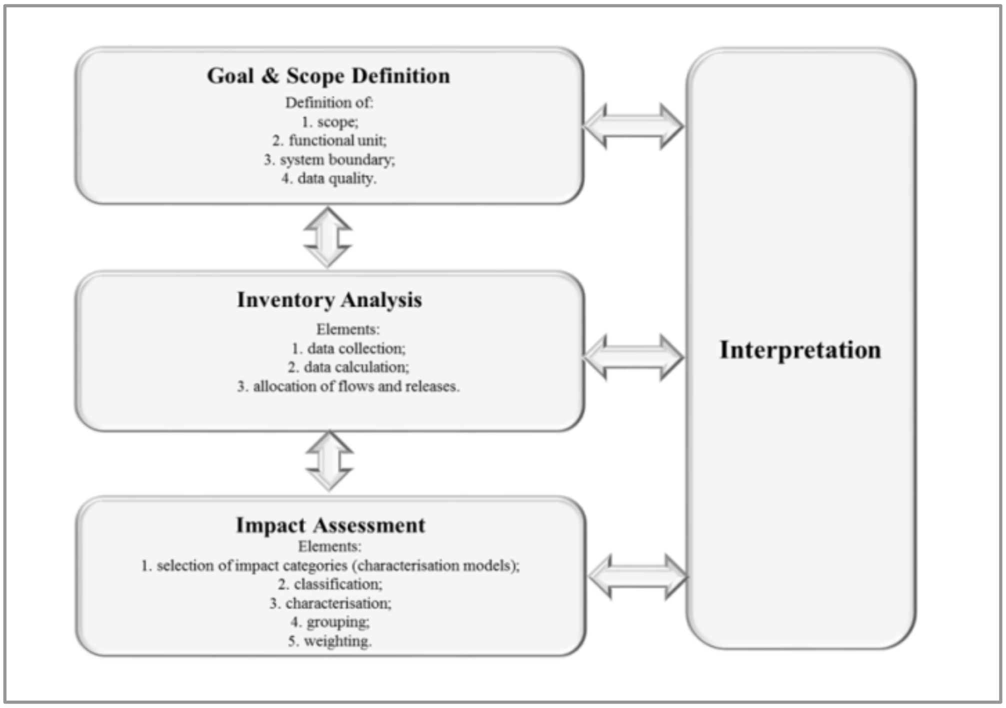
- *the life cycle perspective*: considering the entire life cycle of a product, from the extraction and acquisition of raw materials, through energy and material production and manufacturing, to its use and end of life treatment and final disposal;
- *the interest in the environment*: focusing on environmental aspects and on the impacts of a product / service system;
- *relative approach and functional unit*: the approach is structured around a functional unit, which defines what is being studied;
- *the iterative approach*: allows for the carrying out, in sequence, of the various phases, using for each of them the output of the previous one as input for the next;
- *transparency*: this is necessary in order to guarantee a correct interpretation of the results;
- *comprehensiveness*: an LCA must consider all aspects of the natural environment, human health and resources;
- *scientific approach*: the assumptions and decisions of an LCA must be based on scientific considerations.

3.2.2. METHODOLOGICAL FRAMEWORK

The structure of an LCA, depicted in Figure 24, is divided into four main steps:

1. *goal and scope*: in which the objective and field of application is defined and specified. It is a preliminary phase in which the objectives are defined as well as the scopeof the study, including the functional unit, the boundaries of the system to be studied, the need for data, the assumptions and limits, who performs and to whom the study is directed, what functions or products are to be studied and data quality requirements;
2. *inventory analysis (LCI):* consists of data collection and calculation procedures aimed at quantifying the relevant incoming and outgoing flows of a product, according to the objective and purpose ;
3. *impact Assessment (LCIA):* aims to assess the extent of potential environmental impacts using the results of the inventory analysis;
4. *interpretation*: it is a systematic procedure aimed at identifying, qualifying, verifying and evaluating the results of the inventory and impact assessment phases, in order to present them in a form that meets the application requirements described in the objective and in the purpose of the application and to draw conclusions and recommendations.

Figure 24 – LCA framework as defined by ISO14040:2002 standards.



LCA models the life cycle of a product function, by considering in fact not only just the product itself. The product life cycle consists in a series of sub-processes which are linked together with flows (materials and energy). The simplification of the life cycle into a series of steps, simplifies the LCA analysis in the sense that it facilitates the identification of the inputs and outputs of the product system

3.2.2.1 GOAL AND SCOPE

The UNI EN ISO 10040 standard introduces the following topic: "*The objectives and scope of the study of an LCA must be clearly defined and be consistent with the intended application. The objective of an LCA must establish unambiguously what the intended application is, the motivations that lead to the study and the type of public to which it is intended, that is, to which people it intends to communicate the results of the study* ".

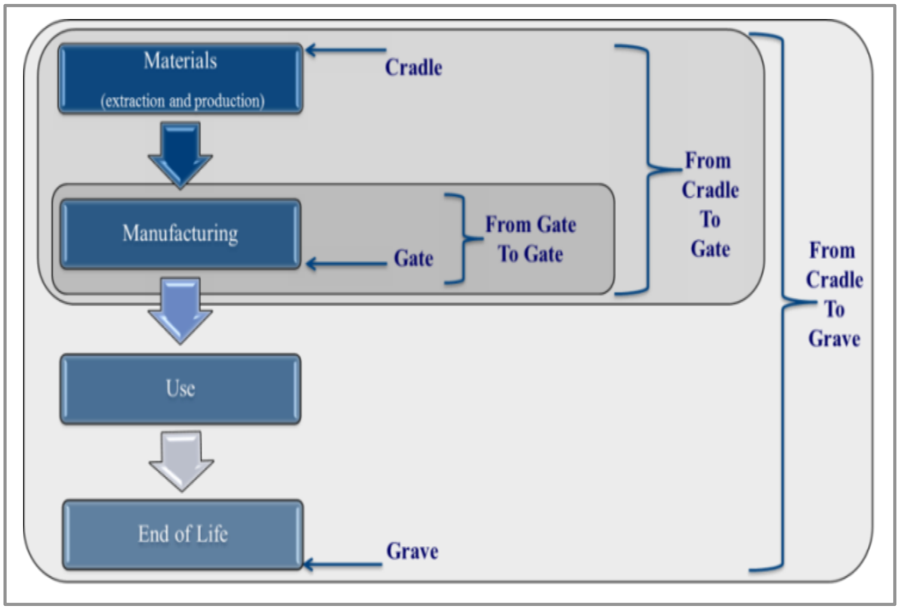
In the Goal and Scope section are defined the: *scope of the study*, *the functional unit*, *the system boundaries*, *the data quality, hypothesis, limitations, type of critical review, type and format of the report required for the study and allocation procedures.*

First of all the *scope of the study* should be explained, for instance whether it has been drawn up to to compare different products with the same function or to plan improvements to an existing solution or to analyze an existing reference solution and so on….Secondly, the boundaries *of the system* (conceptual, geographical and temporal), and hence the level of detail, depending on the scope of the project, should be chosen. If the study is addressed for internal use (improving the environmental performance of the product), a simplified LCA can be produced, which considers only the critical aspects for the subject that produces the LCA; vice versa, if the study is conducted for external use it is necessary to make a more complete elaboration. In addition to the scope of study, what discriminates one choice rather than another is the quality and reliability of the data. The subsequent step is the definition of the *functional unit*, which represents the quantity of product that is used as a reference for the calculations of the flows of material and energy during the inventory phase. It is the product, service or function on which to set up the analysis and indicates the reference object of the study to which all input and output data will be normalized. In fact, the functional unit allows for the comparison of different but functionally equivalent systems.

Based on the portion of the life cycle to be considered, and therefore on any simplifications, four types of study (

Figure 25) can be distinguished and defined as follows: i) *"from cradle to cradle"*, beginning with the extraction of raw materials up to the revaluation of the product at the end of life through the recovery of energy and materials; ii) "*from cradle to gate"*, the study starts with the procurement of raw materials and energy sources and ends with the introduction of the finished product on the market, not including the use phase; iii) *"from gate to gate"* in which only the manufacturing and assembly phases of the product are included, thus limiting the study to the work which is carried out within the company; and iv) "*from cradle to grave*", which includes all the phases of the life cycle, from the extraction of raw materials, to industrial production up to the use of goods, including disposal at the end of life.

Figure 25 - Representation of the various approach considering the system boundaries of the FU.



The most widely used approach is "from cradle to cradle" as we want to give weight to the revaluation of the product through the recovery of energy and materials, with the aim of progressively reducing the amount of waste to be sent to landfill.

3.2.2.2 LIFE CYCLE INVENTORY (LCI)

The inventory analysis is a practical process to collect data, to quantify the inputs and outputs of the system, according to the FU. It is during this phase that information is collected on the energy and materials (also auxiliaries) consumed, as well as the emissions and waste generated and used during each step of the FU life cycle. LCI is based on the functional unit of the analysis and on the system boundary of the product system considered. In order to identify each process profile, the total system is divided into sub-system elementary flows. Particular attention should be given for allocation procedures when dealing with systems involving multiple products and recycling systems.

According to their quality, data are categorized as follows: i) primary data when this refers to precise and directly measured data ii) secondary data, or estimates based on conjecture and iii) tertiary, if data taken from literature are used. Regarding tertiary data, several databases are available on the worldwide platform: i) Joint Research Center (JRC) – ELCD database[20] ii) U.S. Life Cycle Inventory Database – National Renewable Energy Laboratory(NREL)[21], iii) Center for environmental assessment of product and material systems (CPM)[22].

3.2.2.3 LIFE CYCLE IMPACT ASSESSMENT

Life Cycle Impact Assessment (LCIA) is a process for identifying and characterizing the potential effects produced in the environment by the system under study, using the LCI data, the calculation-bases are described in ANNEX C.

The LCIA consists of four main steps: i) *classification* ii) *characterization* iii) *normalization* and iv) *weighting*. The last two steps are not mandatory. The first step is *classification*, which groups the LCI data in different impact categories to which they are deemed to contribute. Indicators of the impact categories are selected, based on the intended study, and generally include topics such as: i) climate change ii) toxicity, iii) ozone depletion and so on…Subsequently, *characterization* consists of weighting the impact substances which contribute to the same environmental impact. Thus, for every impact category included in LCIA, an aggregated result is obtained in a given unit of measure (midpoint result). The third step is *normalization*, which involves relating the characterized data to a broader data set or situation. The ultimate phase is *weighting*, in which the previous results are converted into scores by using numerical factors based on values (endpoint result). This is the most subjective stage of an LCA, being based on value judgments rather than scientific ones. For instance, a panel of experts or the public could be formed in order to weight the impact categories. The advantage of this stage is that different criteria (impact categories) are converted to a numerical score of environmental impact, thus making it easier to make decisions. At present the major Impact Assessment methodologies are, for example: TRACI 2.0[23], CML 2016[24], ReCiPe[25], and so on… A proof description of CML method is given in ANNEX D, since it is the method selected for the case studies analysis of the present dissertation.

Each of these methodologies investigates different environmental impacts, and many choose one methodology rather than another, depending on which specific environmental issue is being addressed. In fact, specific environmental categories (addressing a specific issue and using a specific method) are selected according to the reference sector. For example, to highlight the impact in the automotive sector of CO_2 emissions, the GWP factor is commonly used. A new PEF methodology has recently emerged

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[20] http://eplca.jrc.ec.europa.eu/ELCD3/.
[21] http://www.nrel.gov/lci/.
[22] http://cpmdatabase.cpm.chalmers.se/Start.asp.
[23] https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=227747.
[24] https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors.
[25] https://www.rivm.nl/en/Topics/L/Life_Cycle_Assessment_LCA/ReCiPe.

with the aim of making studies and comparison parameters more uniform. This is a synthesis of impact categories identified in the aforementioned methodologies.

This PEF[26] Guide [seeks to]*"Establish a common methodological approach to enable Member States and the private sector to assess, display and benchmark the environmental performance of products, services and companies based on a comprehensive assessment of environmental impacts over the life-cycle ('environmental footprint')".*

3.2.2.4 INTERPRETATION

In the last phase of *interpretation* the results acquired are presented in a synthetic way and summarized.

In this phase the results are delivered in such a way as to be understandable for the public, each impact is analyzed and the main considerations are presented. Moreover, during this phase further action regards the investigation into the reliability of the study, looking at the definition of the FU, as well as the data used and project goal and scope.

3.2.2.5 SOFTWARE TOOLS

As can be assumed from the previous discussion, the implementation of the methodology is highly complex: there are numerous data to collect and numerous analytical models to be implemented. To overcome these computational burdens software tooling is widely used. These have been created in such a way as to have a user friendly structured interface, in order to easily manage the implementation of a representative model of the PSS life cycle. These programmes consist in a rich database of useful information regarding materials, energy and processes with references to their production profiles which have already been modeled and which differ according to the territory. For example, there are different models regarding electricity depending on the territory which produces it. In addition, the software considers the spatial differentiation for the characterization, normalization and weighting steps, which are dependent on the region under consideration. Moreover, the above-mentioned current impact assessment methodologies have already been inserted in the software content so the user does not have to directly manage the LCIA steps, since it is the software, starting from inventory data modeled, which provides the results.

Currently, the most commonly used software at the organizational and academic level are GaBi[27],Simapro[28] and open LCA[29]. The selection of the preferred database is dependent on their database collection.

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[26] http://ec.europa.eu/environment/eussd/smgp/ef_pilots.htm.

[27] http://www.gabi-software.com/italy/index/.

[28] https://simapro.com/.

[29] http://www.openlca.org/.

3.2.3 CRITICAL REVIEW& FUTURE CHALLENGES

The LCA is a tool used to draw up the environmental profile of a product/service system (PSS), in the sense that it maps all the flows generated along the full life cycle, including all the materials consumed, as well as the emissions and releases generated. According to this definition, it could be defined as a system map: these attributes are aiming at a broadening of the debate and reflection on environmental concerns beyond that of a single issue. Moreover, this quantitative methodology allows for an objective comparison between different scenarios, and provides feedback which could be measured and monitored for future calculations. On the other hand, there are certain precautions which must be considered when carrying out this type of analysis, which is not 100% reliable. LCA is not able to assess all the impact implications, since these are limitations on the system boundary and on the time under consideration, on the location and on how the emissions and flows are released into the environment. Clearly, it is not possible to use a customized model; otherwise there would be difficulty in making comparisons and also in getting data to model the environmental profile of all the substances involved. Moreover, a simplified LCA is generally carried out, otherwise the process would become burdensome. All the limitations and hypotheses are reported in *the goal and scope* phase. The impact assessment addresses merely the environmental concerns specified in the goal and scope. Therefore, LCIA is not a complete assessment of all environmental issues of the product system under study. Another matter is related to the impact assessment stage since is not yet possible to address all the environmental concerns and the measurement is based on an analytic approach and a mathematic modelling, which presupposes limitations in the calculations due to the computational difficulties.

3.3 LCC METHODOLOGY

LCC has been defined as a methodology which incorporates all the costs (incoming and outgoing), relating to the quantification of internal and external items associated with the life cycle of a product and are directly related to one or more actors in the supply chain.

The US General Accounting Office firstly used the LCC methodology in the 1981 (Sherif Y.S. and Kolarik W.J., 1981) and forty years later it attracted attention within the European public sector context(UNEP, 2011).At the beginning, the LCC was commonly applied for limited sectors: i) mostly buildings, for commercial or public purposes ii) for the generation and use of energy iii) the aerospace sector during assessment of investments but iv) mainly for military equipment and weapon systems.

Later on, the scope of the methodology was broadened to support decisions during the development of new products and in the evaluation of strategic funds to calculate the economic convenience of alternative investments (Ciroth A., 2003).

3.3.1 GENERAL DESCRIPTION

A well-accepted definition is provided by Rebitzer and Hunkler (Rebitzer D. and Hunkler G., 2003) who defined the term Environmental Life Cycle Costing 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 (…) with complementary inclusion of externalities that are anticipated to be internalized in the decision-relevant future"*.

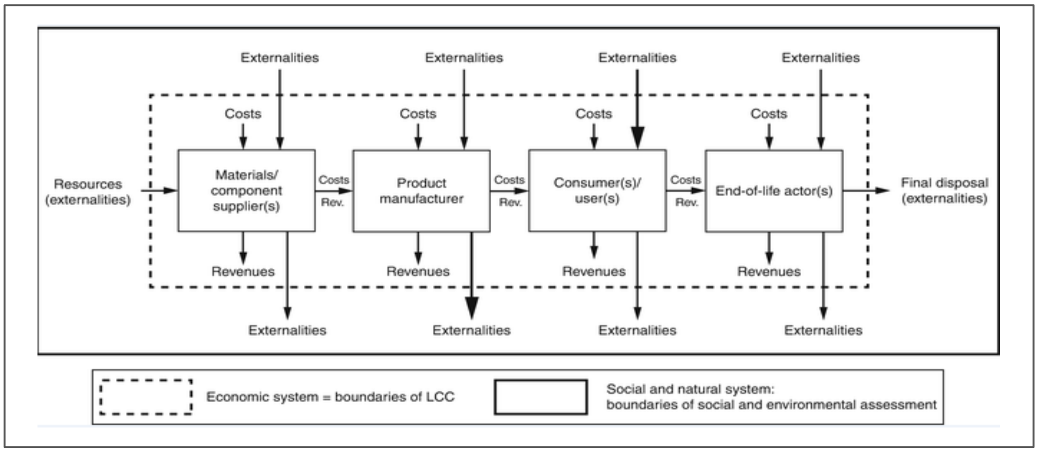
The LCC has a function-systems orientation with regard of to the life cycle perspective. In this sense, Life Cycle Costing (LCC) has been suggested as a consistent frame for combining LCA and economic assessment. Indeed, the two methodologies share various similarities. As regards the scope, there is not much difference, since both methodologies are based on the perspective of the concept of "Life Cycle" analysis, therefore considering all the processes connected to the physical life cycle of the product. What differs is the object of investigation, thus the nature of flows typology is considered. Unlike LCA, which takes into account environmental attributes, the LCC is based on the calculation and quantification of the costs directly impacting the decision maker, so the unit of tracking flows is expressed in monetary units. Monetary cost can be defined as the value of goods and services that are purchased (real money flows) (Swarr T.E., 2011). Another relevant difference is the time horizon considered, since in the LCC the period of time within which the costs occur has to be considered. For that reason the discounting of costs and investments is applied in order to calculate the present costs that will occur in the future. However, LCC should be complementary and consistent with the equivalent environmental assessment (Rebitzer D. and Hunkler G., 2003; Huppes G., 2004). In fact, from the contextual application of the LCA and LCC could be obtained synergies, starting from a framework description (Testa F. et al, 2010).

According to SETAC-Europe Working Group on LCC(UNEP, 2011), three distinct approaches can be distinguished: i) conventional LCC (cLCC), environmental LCC (eLCC) and social LCC (sLCC).

The central difference is in terms of the types of costs, which, in the typical *conventional LCC* application is mainly focused on its own budget costs, while in *environmental LCC* the focus is on the costs of all life cycle stakeholders (existing or anticipated). The first approach assesses all conventional costs associated with the life cycle of a product that are directly covered by a given actor in the life cycle and includes internal (not external) costs The perspective used is generally of the producer or of the consumer. The environmental LCC (eLCC) adds on to the conventional LCC all the costs attributed and generated by the projection of future externalities that will occur. An environmental LCC (eLCC) builds upon conventional LCC and covers the external costs which are covered by externalities (Carlsson R.M., 2005).The last approach is the social LCC, which assesses the potential costs associated with the life cycle covered by the actors in society. Its basis is the eLCC plus the additional assessment of further external costs. The perspective is from any actor in society, including government and a single score will be applied for all dimensions of sustainability.

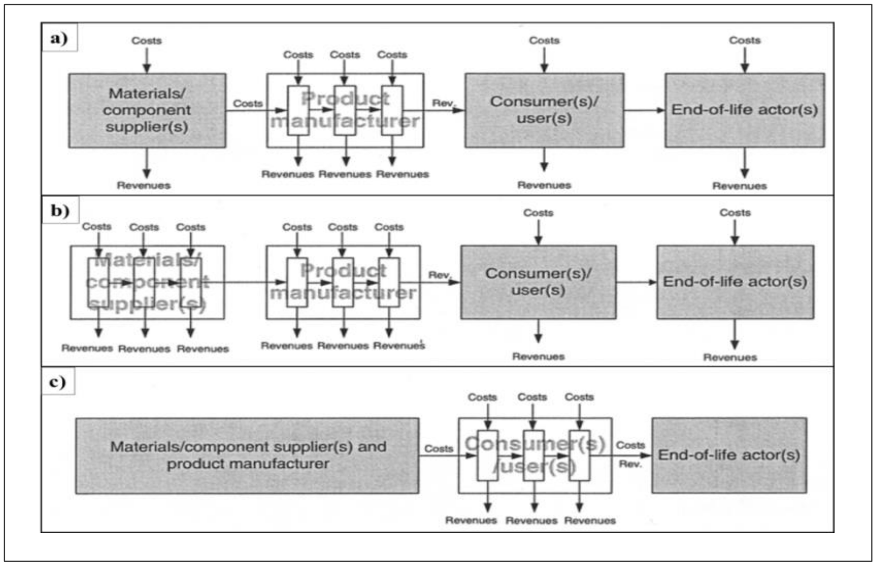
Generally speaking, the two main categories of costs relating to environmental damage and damage-avoidance are: i) those already existing externally but which have yet to be internalized (with a recognized monetary value), including environmental services, environmental and energy coordinators, corporate environmental programs and initiatives, waste minimization and pollution prevention, fines and procedures, environmental taxes (for reclamation, disposal, effects on the climate) and environmental savings (energy saving measures, reduction of water consumption, reduction of packaging costs etc.) ii) the anticipated external costs which are to be internalized in the near future and which are relevant to the decision maker (typically not covered in market transactions), including the spheres of health and social well-being, the quality of the work environment, impacts on family and social life and impacts on material well-being. Among the three distinct approaches, the conventional and environmental ones are at an advanced stage, while the development of the social impact of a product is still at the embryonic stage. The reason behind this is that, when extending eLCC to the social LCC, a broad social perspective has to be integrated and so the monetary objects are geographically-dependent and have to take into account site-specific guidelines (Testa F. et al., 2010). So the system boundaries considered are not the same (Figure 26) since in the eLCC and sLCC, they take into consideration the entire life cycle for their definition while in the cLCC some aspects (like EoL) are not always included. Another factor is the inclusion of externalities, which are excluded in the cLCC (only internal costs are considered) and so, for the calculation of future external costs in the eLCC and sLCC, the discounting procedure is considered (Hoogmartens R. et al, 2014).

Figure 26 – eLCC System boundary (Rebitzer G. and Hunkeler D., 2003).



The reason for the inclusion of certain costs is due to the different perspectives of the three methodologies (Figure 27) since, in the cLCC and eLCC, the consumers' and manufacturers' perspectives are considered, while the sLCC is based on governmental and social points of view. In this sense, the reference of investigation is different since for the cLCC and eLCC it is a product or system, while the sLCC considers the total system. In short, to broaden cLCC, the key aspects are: (i) the purpose of the assessment (ii) the time period taken into account and (iii) the use or absence of discounting to deal with long-term horizons (Hoogmartens R. et al., 2014).

Figure 27 – Different perspective in LCC according to: a) product manufacturer; b) product manufacturer and supply chain; c) consumers/user/s (Rebitzer G. and Hunkeler D., 2003).



3.3.1.1 APPLICATION AND SCOPE

The choice of the LCC typology depends on the object of interest and whether the focus should be related to the cost factors and/or should embrace environmental or social monetary elements. Furthermore, it depends on the target audience: within the company context the cLCC and/or eLCC are commonly carried out, whereas if the audience is more extensive (i.e. for governmental purposes), then the sLCC approach is adopted.

3.3.1.2 REFERENCE STANDARDS

Until now LCC has developed, taking its inspiration from all the results of specific case study applications rather than models, which have never been clearly developed. However a few standards do exist e.g.: ISO 15663, IEC 60300-3-3, etc. for specific application purposes.

3.3.2 METHODOLOGICAL FRAMEWORK

The Society of Environmental Toxicology and Chemistry (SETAC) working group published a code of practice to carry out LCC. It took its inspiration from the LCA framework, without imposing the full product life cycle as a system boundary. Therefore, the "Code of Practice" suggests following four main steps: i) *definition of goal and scope* ii) *economic inventory* iii) *interpretation* and iv) *reporting and review*.

3.3.2.1 THE DEFINITIONS OF GOAL AND SCOPE

The first step is to define the intended application and audience, according to the following characterizations: *goals, functional unit, perspective and system boundaries.* Examples of potential goals could be the attribution of costs from a particular perspective: internal management costs for a company, for investment purposes…. For *functional unit* is intended the reference to which all costs and benefits are related. The perspective definition could include producer, customer, stakeholder or governments. Lastly the *system boundaries* express which stages of the life cycle are to be considered in relation to the perspective.

3.3.2.2 INVENTORY

In this phase all the costs related to the product life cycle have to be identified and classified. In this sense the LCI model from LCA can be used effectively for cost inventory purposes. The inventory phase regards gathering the various cost flows generated to produce the various single functional units during the whole life cycle. Following the well-known cost classification of the US-EPA (Environmental Protection Agency), the following costs sustained by an organization can be distinguished: conventional costs (direct costs such as acquisition of materials, labour costs…), potentially hidden costs (indirect costs such as overheads related to waste treatments and production facilities, pollution controls), contingent costs (uncertain future costs of environmental remediation and EoL …) and image costs (Testa F. at al., 2010).

Sources for data gathering depend on the nature of the costs: if they are internal costs they could be quantified within the company perimeter; instead for others an external database and different calculation methods with estimations and forecasting should be used. The necessity to use an external database, which also collects data that are different and site-specific, could represent an issue when the purpose is a comparative analysis. A widely used model which has estimated the upstream GHG emissions, is the Transportation Fuel Cycle Model (GREET[30]) developed at Argonne National Laboratory.

Moreover, valuations of specific environmental damage costs (expressed in cost unit/quantity) are based on studies carried out under the auspices of the European Commission's ExternE[31] Programme.

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[30] https://greet.es.anl.gov/

[31] http://www.externe.info/externe_2006/

The ExternE studies concern the costs of air-pollutant damage which affects human health associated with the effects of small particles in the air that are either emitted directly in fossil fuel combustion or are formed by reactions in the atmosphere of gases generated from exhaust pipe emissions. These estimations are based on the consideration of direct medical costs and on the ‘‘willingness to pay’’ to avoid air-pollutant health damage for people. This model is used in the context of sLCC analysis, to reflect on possible technologies, bolstered by public policies, to pursue the reduction of external effects relating to today’s new cars.

3.3.2.3. INTERPRETATION

The aim of this step is to evaluate the results obtained. The LCA interpretation phase can be used as an inspiration to this extent.

3.3.3 CRITICAL REVIEWS & FUTURE CHALLENGES

The most challenging aspect, when carrying out an LCC analysis is the lack of a standardized skeleton, thus making it difficult to obtain objective data, for external use and for making comparisons between different scenarios. Moreover, since the nature of the analysis is strictly objective, when the perimeter considered is within a company and/ or business-oriented perspective it could be considered inconsistent for integration in a broader LCSA analysis. In this context, the role of the LCC has been strongly criticized as not being a representative pillar for the economic dimension of sustainability. Another reason is due to the fact that LCC primarily considers the individual rather than the global costs. Even though there has been an explosion of sustainability assessment tools involving the LCC aspect, ambiguities in the application and the data used create ambiguity and confusion. Moreover, the integration within the broader context at macro-level is certainly complex, especially for the sLCC (Testa F. at al., 2010).

One potentially challenging aspect that LCC attempts to encapsulate is the LCC cost perspective, in fact there is the risk of double counting. Moreover, data on costs may reflect different periods of time, while some costs should occur in different periods of time and therefore a methodology such as discounting should be preferred. The current costs, influenced by external effects, taxes and subsidies, are considered to be an insignificant element for providing an indication of sustainability.

3.3.4 LCC CASE STUDY APPLICATION

In the present section some applications and selected literature from academia and practitioners are given (Stella L. et al, 2014), regarding the LCC at a general level and also rooted in the automotive context. Some investigations focus attention on the economic advantages of considering different fuel options, whereas others focus attention on different modes of manufacturing. Still others attempt to find a useful formula in the calculation of sLCC. Most of them point out that LCC applications are far from ideal; despite many study applications available in this field; no systematic analyses on actual implementations exist.

In addition, the analysis is still at the level of details and does not cover the whole life cycle; most of the time the costs reported have previously been estimated by others (expert opinions), methods based on expert opinion rather than statistical methods. Besides this, due to the uncertainty of the origin and reliability of costs, it is worthwhile considering a sensitivity analysis rather than one with a deterministic estimate. Due to the lack of certainties, conclusions from an LCC analysis should be carefully weighed (Korpi E. and Risku T., 2008). However, in the automotive context, especially at the vehicle level, it is difficult to balance a holistic optimization over the life-cycle, since numerous factors are involved (stakeholders, manufacturing complexity, materials' breakdown) and their results are difficult to determine (Bornschlegla M. et al., 2015). Most of the time, it is preferable to simplify by reducing calculations to the bare minimum (Rush C. et al, 2000;Cicconi P. et al, 2014). Some authors affirm the importance of the use of the LCC instrument at an early planning stage, to provide a supporting tool for strategy decisions which, starting from customer requirements, through pre-design, production, assembly, testing, shipment and re-assembly, cover the entire product life cycle stage.

Several studies report that frequently the use of innovative and more sustainable materials results in a higher acquisition cost. However, an offsetting effect is represented by the cost of the reduced amount of fuel required (usually the life span is considered to be about 150.000 km). The trade-off between the cost of materials and manufacturing depends on whether a consistent costs-saving during use manages to counterbalance the material cost increase of the innovative solution. Despite the high purchasing costs of the materials, the total LCC costs frequently turn out to be cheaper if the use phase and/or the end-of-life phase are taken into account. Thus, the LCC can support clients to make right choices, and assist producers to spotlight the financial advantages of buying an environmentally preferable product (Klöpffer W. and CirothA., 2011). Other authors have used the LCC analysis to calculate the economic impact of different fuels in transportation from a social perspective; some examples are (Hekker M et al., 2003; Odgen J. et al, 2004),and regarding vehicle use (Lipman E. and Delucchi M.A., 2003).

Recent studies are now focusing attention on the vehicle technologies to be made available in the near future, by analyzing a model with a consumer LCC perspective. With this aim in view, not only the vehicle's initial cost and operation are considered, but particular attention is given to the calculation of external costs, thus performing a sLCC. Generally, the external costs considered are due to pollution damage (Goedecke M. et al, 2007) while others also include vehicle maintenance, and uncertainty concerning oil supplies (despite asserting their uncertainties as to the use of this method) (Odgen J. et al, 2004).Other authors point out that cost calculations depend on the geographical area, because of the differences in taxation, the price of petrol, electric power and pollution (Panos D. and Lambros K., 2016).All the aforementioned studies consider in the calculation of external costs the effects due to emissions from the following substances: carbon dioxide (CO_2), methane (CH_4), nitrous oxide(N_2O), greenhouse gas (GHG), volatile organic compounds (VOC), carbon monoxide (CO), nitrogen oxides (NO_x), particles of matter with a diameter of less than 10μm (PM_{10}), sulphur oxides (SOx).

3.4 S-LCA METHODOLOGY

Compared to the two previously discussed methodologies, the social impact analysis shows considerable immaturity and, for the moment at least, does not allow a real standard to be defined in this connection. In fact, there are numerous discussions and issues concerning the uncertainty of the methodologies proposed today.

3.4.1 GENERAL DESCRIPTION

The S-LCA was first defined by UNEP/SETAC (2009) (UNEP-SETAC, 2009)as *"The impact assessment technique that aims to assess the social and socio-economic aspects of products and their potential positive and negative impacts along their life cycle".* The S-LCA guidelines have been developed following the guidelines promoted by the UNEP/SETAC, which has promoted several initiatives to provide more detailed and practical examples for an effective methodological applicability. At present, the proposal for the most comprehensive and practical methodology has been made by the Roundtable for Product Social Metrics initiative, coordinated by PRé Consultant. The working group has established a new methodology through gaining an understanding of the various methods and standards (GRI, ISO 26000) which have already been applied by those involved as decision-makers. The actors involved are experts in the social sustainability field from companies, especially the automotive sector. To be specific, the guiding principles were defined to establish a social analysis at the product level.

In short, the S-LCA is a method that can be used to assess the social and sociological aspects along the life cycle of the product, from the extraction of materials and their processing to the final disposal of the product.

3.4.1.1 APPLICATION AND SCOPE

From the S-LCA results a great deal of information can be retrieved regarding the socially responsible behaviour of a company. Moreover, since the method's view point is from a life cycle perspective, the behaviour of the various actors involved (such as local communities, workers and consumers) is taken into account. In fact, the analyses also encompass the surrounding perimeter and usually include geographic information and conditions referring to the assessment of the external stakeholders (consumers, local communities…).

Overall, the S-LCA provides information about the potential and effective social impacts on stakeholders caused by the activities in the life cycle of their product. Normally, the social responsibility is strictly related to the companies' behaviour rather than the technology of the processes. The results of the social analysis are useful to provide more insight into company policy behaviour and indicate hot-spots with respect to the social sustainability aspect. Thus, companies could contribute to improving the social performance of products at different stages of their life cycle and so bring about innovations in processes and products to conquer new market segments. For consumers and governmental organizations the social analysis is useful for gaining more awareness and to help consumers to be critical and responsible while making informed choices. In particular public decision-makers and organizations could formulate sustainability policies based on concrete scientific data. At present, no way has yet been established to properly define the product system in the social analysis. However, two different approaches have been suggested as to procedure (Dreyer L. et al, 2005). The first is the so-called *technology-oriented approach*, which is based on an LCA methodological sheet, which splits the product life cycle according to its technological steps, considering the same FU and system boundaries as LCA and basing the principals for the calculation of allocation on the environmental flows; the reference indicators selected are those taken from the guidelines. The second suggestion is the *organization-oriented* approach, which is more customized and is principally based on the major key-stakeholders involved (Jørgensen A. et al, 2008; Dreyer L.C. et al, 2010). In the latter model it is the company itself that decides as a reference unit of assessment the stakeholders rather than a physical product. This is also the case for the impact indicators and allocation methods. In the selection of the most effective approach, it is the company that needs to counterbalance the positive or negative drawbacks. Actually, the technology–oriented approach does not reflect the stakeholders' contribution and some disagree as to the effective association of physical systems (physical flows) and social aspects (Martínez-Blanco J. et al, 2014).

However, the selection of the organization-oriented approach may lead to the difficult association of the various stakeholders' effective contribution to the specific product life cycle phase, thus leading to a shortening of the system-boundaries of the analysis. The selection of the specific approach involves consequences regarding the selection of the system boundaries to be considered.

3.4.1.2 REFERENCE STANDARDS

In the application of a social assessment analysis two approaches are commonly adopted. The first one investigates the social performance of the company excluding the life cycle view, whereas the second takes its inspiration from the LCA framework. In the present section the more objective UNEP/SETAC method is discussed in depth, in which the whole life cycle of the product analysis is considered. The two technical documents to use as practical guidance are the "Guidelines for Social Life Cycle Assessment of Products" and "The Methodological Sheets for Subcategories in SLCA» (UNEP/SETAC 2013) (UNEP/SETAC, 2013) and reported in brief in ANNEX E.

3.4.2 METHODOLOGICAL FRAMEWORKS

SLCA is in line with the ISO14040 and ISO14044 structures proposed for LCA. Thus, it is structured according to the following sub-divisions: i) *definitions of goal and scope* ii) *life cycle inventory* iii) *characterization* and iv) *interpretation*. The first phase of the *goal and scope* defines the: functional unit, system boundaries, impact indicators, data quality (based on whether the qualitative or quantitative approach is selected), stakeholders' categories and method of allocation.

3.4.2.1 SCOPEAND BOUNDARY

Identifying the right functional unit is not so simple, in particular, how to link it with social indicators (Wu R. et al., 2014). Moreover, a definition of the allocation factor when addressing the impact of a product on social indicators is not so direct and strictly depends on the management of the company. Another factor is related to the geographical location, since the criteria involved in the definition of the social aspects are different when promoted by government regulations, policies and company standards. Particular attention has to be paid to the data source which differs according to the various stakeholders since it depends on many variables: allocation methods, specific regulations and data availability. The data selection may be qualitative or quantitative. In addition, particular care must be taken in the selection of the system boundaries, especially if social analysis is integrated within the broader LCSA framework.

3.4.2.2 LIFE CYCLE INVENTORY ANALYSIS

The most challenging phase of all is that of the collection of data. In the first place, it is extremely heterogeneous, since each formula and feature is strictly rooted in the company's perspective and in its geographical background. Moreover, a notable effort is required to scale down data from global valuations to specific contributions. A proper data collection should be carried out with particular attention to the auditing approach which, of necessity, needs great accuracy in the design of data, while taking into account the contextualization of boundary conditions: location, sector, size….

Regarding the typology of data used: when it is difficult to get primary (subjective) data, a worldwide database is used to obtain secondary (objective) information. The best-known hotspot assessments, which include generic data combined with sector-country-specific assessments, including tools such as the Social Hotspot Database (SHDB) and the Product Social Impact Life Cycle Assessment (PSILCA).

3.4.2.3 IMPACT CATEGORIES

In the impact assessment phase the inventory information data are translated into impacts according to the categories selected. Therefore, the impact phase, as for the LCA, includes the specification of indicators selected followed by classification, characterization, normalization and weighting. However, the scoring and weighting arrangements represent an important gap in SLCA (Benoit-Norris et al, 2010) since no method or guidelines are provided for this purpose(Benoit-Norris et al., 2011).

Inventory data are aggregated to a midpoint or end-point level through causal-effect chain modeling.

As regards the automotive sector, no impact categories are suggested to assess the social impact on consumers during vehicle/component use. This may be due to the fact that it is difficult to prove any social implications linked with the user and the product. In the selection of potential impact indicators, a combination of the top-down and bottom-up methods is suggested. According to the first method, the identification of the impact categories takes its inspiration from the main world-wide social and socio-economic issues, whereas in the second they are selected according to the state-of art on social data measured at company level (Kruse et al, 2008; Dreyer et al, 2005). The indicators designed according to the first approach may not represent the point of view and the priorities of the people/communities affected by the impacts considered, in contrast to the bottom-up approach, which could give rise to both incomplete and complete sets of indicators. For S-LCA cases, qualitative and quantitative indicators could be used, or a mix of them. Most of the studies count on the indicators proposed in the UNEP/SETAC guidelines (Vinyes et al., 2012;Martínez-Blanco et al., 2014).

Another instrument of inspiration for carmakers is the materiality principle, through which the company's and stakeholders' points of view on specific themes can be measured and integrated. Among the similarities in the different approaches there are some characteristics that define social indicators: i) they should measure negative and positive social impacts, they can be either quantitative (when the social aspect considered is given in numerical terms), qualitative/descriptive(when the social aspect considered is expressed through adjectives or qualitative evaluation) and semi-quantitative (when the quality classification is given through an evaluation scale or through a yes/no evaluation).

3.4.2.3 INTERPRETATION OF IMPACTS

The interpretation of the results regarding characterization should be made with great care, giving the specification and description of each score. Moreover, quantitative results are expressed in percentages while others are in numbers, so there is no common criterion. Another factor is related to the ambiguity of the results, since high scores do not always imply a good performance (i.e. the number of accidents…).

3.4.3 CRITICAL REVIEW & FUTURE CHALLENGES

The shift from LCA to S-LCA is not so obvious; there are substantial differences regarding the disciplines which study environmental impacts. Natural phenomena are mostly predictable and measurable while social phenomena are influenced by numerous factors and cannot therefore be attributed directly and solely to the nature of production processes, since they are often linked to the behaviour of actors and/or territorial contexts.

In the environmental and social analysis, there is a direct correlation between cause and effect; in the social analysis, the impacts can be caused not only by the production of the component but also by how the process is managed by the company. For this reason, the correlation can be misleading in the association of the social impact deriving from the production of that specific product.

Assessing the social dimension of sustainability is a very complex issue: the unit assessment is extremely heterogeneous. In fact, there is a wide diversity of indicators which can cause confusion and hinder understanding. It is difficult to define a common set of indicators.

Furthermore, the lack of factors regarding characterization does not easily allow inventory data to be transferred into impacts. No standards are provided and this makes for difficulties in the implementation and in the comparability of the assessment. Another issue is the inventory, since data collection is demanding and above all is not easy to find, so a qualitative approach is preferable: a representative selection of data is used, which is strictly dependent on the context and the geographical position. The dearth of data worldwide represents an obstacle to obtaining a full and reliable analysis of the results. The carrying out of a social analysis by a company is difficult and burdensome due to the inability of companies to verify their suppliers and because they lack the means and power. Companies tend to see their social responsibility for the product more broadly than what a life cycle analysis requires, in which only the impacts closely linked to the product life cycle are considered. Due to the launch only recently of the SLCA there is still much room for improvement in the definition of an appropriate methodology to implement social analysis. Certainly efforts should be concentrated on the development of a full and comprehensive common database with guidance on collecting site-specific data. Further provisions should be related to the consolidation of the social approaches (function-orientation and company-orientation) aimed at eliminating the negative effects of both methods while favoring the positive ones. For this purpose, more applications would be useful in order to define a valid set of indicators with data availability, using a bottom-up procedure, thus promoting and disseminating social LCA information at company level.

3.4.4 INSIGHTS FROM CASE STUDY APPLICATIONS

At this point a review of selected literature carried out during the last 10 years on the theme of S-LCA analysis will be presented. Although the S-LCA is defined as the method used to measure the social impact of a product along its life cycle and should support decision-making, there is no proof of its use as a decision support instrument (Jørgensen A., 2013). Although the SLCA approach has the potential to support the decision making process, at the present-day it consists of an over-simplified assessment, which cuts out most parts of the subcategory indicators.

The most discussed topic is undoubtedly the weakness of social methodology due to a lack of suitable assessment instruments and methodologies. Moreover, there are still only a few case study applications available from literature on this theme and most of what exists lacks evaluations regarding their application (Zamagni et al., 2011). In all of the documents presented here, the resulting articles manifest evident inconsistencies in the applications. During recent years many authors have attempted to carry out a detailed analysis of the existing literature in this field (Wu et al., 2014) By sifting through more than twenty-five studies, 4 different frameworks/methods were found to have been applied. From a closer inspection the following conclusions were arrived at: there are inconsistencies in many studies due to the lack of a proper data system to support them, there are incorrect definitions of the goal and scope of the analyses (FU and system boundaries were incoherent). Moreover, it was discovered that the same author had implemented different frameworks/methods/models. In addition, stakeholders, like consumers and other value chain actors, are not always taken into account as workers. A harmonization is necessary and is expected in the near future. From the review of other more recent publications (Sureau et al., 2017) it has emerged that up to 14 different S-LCA frameworks have been identified.

The methodological diversity in the application of S-LCA mostly regards the cause-effect relationships (Bocoum et al, 2015; Iofrida et al., 2017) and the multi-criteria evaluations (De Luca et al, 2015).

Other relevant challenges which have emerged regard how representative the data being used are, since they are associated with various cultural and economic particularities of the countries where the products are sold. Better data models and sources need to be developed to facilitate product comparisons.

But it is also difficult, once inventory data has been obtained, to characterize their relative impact. The selection of the indicators is far from simple for the following reasons: (i) there is no clear distinction among impact indicators and inventory (Neugebauer et al., 2014), (ii) a robust approach for the selection of indicators is seldom discussed and reported in a transparent way

However, the latest methodological applications, follow more context-specific approaches (Del Duce et al., 2013) since they offer the opportunity for encouraging their applicability among organizations and strengthen a decision support role in day-to-day management.

Despite a surge in studies in the discipline of SLCA, many methodological deficiencies still exist which need to be resolved in order for a widely accepted framework for SLCA to be developed (Wang et al., 2016; Tsalis et al., 2017). In particular, the main weaknesses of the SLCA approach are related to the selection of the appropriate data and social indicators, the inclusion of stakeholder groups and impact categories, as well as issues regarding the impact assessment methods (Benoit-Norris et al., 2010; Martínez-Blanco et al., 2014).

Other authors have focused attention on the calculation of the single score, in particular Do Carmo et al., (Do Carmo et al., 2017)have set out a customized scoring and weighting approach for impact assessment with the help of experts. This weighting method is not for a specific sector application and could be used by all types of industries. A few studies take their inspiration from the GRI guidelines and from documents used to assess CSR for selecting impact indicators since these kinds of reports are based on widely accepted sustainability principals which also use specific indicators to accurately define aspects of corporate social performance across the supply chain.

The automotive industry was found to have a high maturity level in the life cycle based sustainability assessment. It included, however, only a small number (Zanchi at al., 2016). An in-depth review of 67 publications up to 2015, focusing on case studies in the automotive sector, is offered by (Zanchi at al., 2016); according to the authors, in order to face the dynamic sets of challenges posed by the application of social analysis rooted in the automotive sector, a road map needs to be considered for driving S-LCA application decisions. Moreover, the authors suggest using as a road map, an organizational perspective approach, which should drive key decisions during the social analysis stream workflow.

3.5 LCSA METHODOLOGY

> *"As far as the laws of mathematics refer to reality,*
> *they are not certain; and as far as they are certain,*
> *they do not refer to reality." — Albert Einstein*

Some authors consider the LCSA methodology an extension of the first environmental LCA (E-LCA) to include an analysis of economic and social aspects, but keeping the basis and the primary inspiration of the LCA methodology. Others in the scientific world have a different perspective and consider the concept of LCSA as a trans-disciplinary framework for the inclusion of various models rather than being a real model in its own right. Considering the latter perspective, the LCSA not only intends to broaden the scope of the indicators but also seeks to extend the object of the analysis, which will be contextualized at the sector level, and will deepen the modelling so as to better characterize them and include more mechanisms. However, the challenge is to draw up, select and make feasible the implementation of the aforementioned disciplinary models, which are applicable to different types of lifecycle questions. Here we adopt an assessment to remain close to the ISO definition of LCA.

3.5.1 LCSA FRAMEWORK

At present the structure and execution of the LCSA analysis is still at the conceptual level and a lot of work must be done to be made operational. Undoubtedly, the increased interest and dedication in conducting these studies can help to increase awareness of the tool. There are two currents of thought in this sense. One is the bottom-up approach, starting from case studies and arriving, by synthesis, at the most representative structure possible. Another method is top-down and starts from a structure which has been defined a priori and, thanks to the implementation of the pioneering case studies, traces the weak points and tries to improve them. The present discussion starts from the assumption of a top-down approach. The LCSA works with a plethora of disciplinary models: the challenge currently consists in structuring, selecting and trying to synthesize the current models available in relation to different types of questions on the sustainability of the life cycle. Although there is no one single method for conducting SLCA, a possible solution is to take the cue from existing models and separate the various environmental issues and then try to summarize them. It has been suggested that the starting point should be the individual analytical tools, the LCA, LCC and S-LCA. Several frameworks have been proposed for the assessment of sustainability with a life cycle approach. Some rules and directions must be applied in order to fully satisfy the LCSA concept, such as the separate applications of methods sharing the same functional unit and equivalent system boundaries and the concept of "strong" sustainability. However, the different methods are still at different levels of maturity (LCA is standardized by the ISO 14040 but LCC and S-LCA have only guidelines at present) making it impossible to structure an effective LCSA method. UNEP / SETAC provide guidance on how to carry out an evaluation through the joint application of the current three LCA, LCC and S-LCA methodologies. According to this criterion, to comply with an LCSA analysis the three methods must converge and harmonize through SETAC coordination and ISO standardization. This framework is based on the ISO 14040 life cycle assessment framework for the LCA environment and comprises four phases: Phase 1 Objective 1 and Scope, LCSA Phase 2 Inventory, Phase 3 Impact Assessments and Phase 4 LCSA Interpretations.

When defining the objective and scope of the LCSA analysis, a single objective and common scope must be considered, although the objectives of each technique may be different (Valdivia et al., 2013), depending on the methodology selected (LCA - energy, LCC - monetary, S-LCA - social criteria).

3.5.2 CASE STUDIES APPLICATION

In the application of LCSA analysis, several authors have developed a procedural approach to implement the LCSA framework. Guinée et al. (Guinée et al., 2011) take inspiration from the well-known LCA model; therefore, the model encompasses three phases: goal and scope definition, modelling and interpretation. In the modelling of each environmental, economic and social aspect, various methods are integrated and merged into one. The workflow consists of a decisional map where there are some questions that must be resolved in order to move on to subsequent implementations: in this sense the author has given a clear guide on how to manage all the information and arrange it so as to create a more structured and operational model. Hu et al. (Hu et al., 2013) have divided the workflow into 5 steps, starting by modelling the technological system at the micro level and then scaling it up with realistic scenarios. In the application of case studies many authors have proved that the combination of the three methods (LCA, LCC and S-LCA) are useful in addressing the sustainable performance of global products, thus providing tangible results for decisions making.

Nevertheless, some authors believe that the development of appropriate quantitative and practical indicators for all three major disciplines need to be empirically based (Kuhnen at al., 2017), reducing and simplifying the context of the number of indicators (Neugebauer et al.. 2015) to be specifically selected in the communication of results (Traverso et al., 2012). When starting to apply LCSA, the most critical challenges, pointed out by many authors, regard the techniques of normalization, weighting, and aggregation(Gloria et al., 2017). In tackling this problem, the application of many case studies has revealed a tendency toward the Multi-Criteria Decision Analysis (MCDA) approaches for both midpoint and endpoint methodologies (Wulf et al. 2017; Grubert E., 2017)investigate preferred practices to obtain single scores. Nevertheless, some discuss the ability of multi-criteria decision analysis (MCDA) to provide a framework for interpreting results and this raises some important questions: whether the three dimensions (environmental, economic and social) in the LCSA analysis should be distinguished at the inventory level or the impact assessment level. The proposed multi-criteria decision of (Jingzhen R. and Toniolo S., 2018), combined with LCSA, addresses some uncertainties but does not allow multiple stakeholders/decision makers to participate in the process of ranking the alternative.

3.5.3 CRITICAL REVIEW

The LCSA is an instrument, which should help to organize a large amount of data from different fields in a structured way, allowing for the full and comprehensive communication of qualitative and quantitative information on the products, which are used to identify the trade-offs between environmental, economic and social issues. In short, promoting this method encourages the awareness of sustainability throughout the value chain in the most complete way. However, there are numerous points of weakness in these methods, due to the difficulties in gaining a full grasp of the dynamics of the complexities intrinsic in the whole sustainability assessment. The methodology is highly fragmented: the final analysis is based on the properties of the parts and not on their interactions.

Undoubtedly, a technique with a more solid scientific base is required to generate knowledge for a better understanding of the life cycle product systems.

In particular, the following areas need to be improved and developed: firstly the definition of the methodological development, detailing the individual steps to be followed one at a time; also, the type of datasets to be used (many databases and data at present in use are unrepresentative, heterogeneous and from different sources, especially as regards social analysis). Lastly, a better definition of the methods used for communicating data, results and applications is necessary.

One of the steps that need special attention is the choice of indicators. For this, it may be useful to draw inspiration from the case studies. Then, once the impact categories have been selected, the criteria for the aggregation and weighting phases must be selected to obtain an overall sustainability score. Critical thinking about standardization, weighting and grouping techniques is at the forefront of LCSA application. To overcome this problem, approaches such as MADM are used as a method for aggregating and switching from midpoint to endpoint results.

From the comprehensive case studies and literature analyzed by (Guinée, 2016) the following challenges can be summarized:

-the need for a common database and unique methods, especially regarding LCC and Social LCA;

-the need for practical (case study) examples indicating how to put LCSA into practice and how to communicate LCSA results;

-the need for more dynamic models;

- trade between the different perspectives of the stakeholders involved.

3.6 CONCLUSION

Case studies are encouraged in order to gain experience from the practical application of all the methodologies. Indeed, there is much room for improvement. The choice of a structure and a consolidated model could be retrieved from a bottom-up approach, i.e. from the application of various case studies or from a top down approach. Certainly many difficulties exist in the correct harmonization of the LCA, LCC and S-LCA methodologies, but also in the last two methodologies themselves. There are a number of different criteria and scales used which make it difficult to model a structure in an analytical way. Furthermore, it should be considered that some analyses are carried out in a more sector-oriented way.

4. THE COMPANY

> *Just as energy is the basis of lifeitself, and*
> *ideas the source of innovation,*
> *so is innovation the vitalspark of all human*
> *change, improvement and progress.(Theodore Levitt)*

Magneti Marelli's mission is to develop hi-tech systems and components devoted to the automotive market. Besides the target of technological innovation, the vocation for quality and excellence is combined with a broader vision for a more sustainable setting.

The following chapter introduces Magneti Marelli$^{©}$(hereafter called MM) focusing on sustainability initiatives carried out in recent years as well as forthcoming sustainability plans and actions. MM is committed to developing its products with the aim of reducing any impact caused by them on the environment and society.

In this regard, attention is given to the questions relating to the evaluation of the product impact according to the LCA, eLCC and S-LCA methods. For this purpose, a broad-spectrum description of the main modalities adopted during the various case study applications is described in the next chapter.

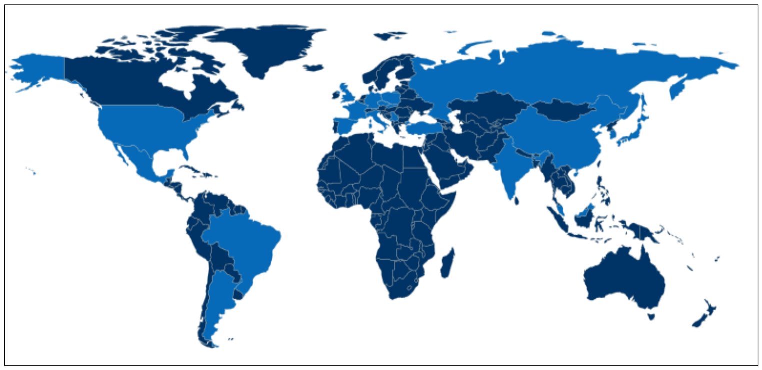
4.1 CORPORATE INFO

Magneti Marelli is a worldwide automotive parts-supplier company, committed to the design and production of hi-tech systems and components. Magneti Marelli was founded in 1919 and is currently based in Italy (Corbetta, Milan).

The Group is present in 19 countries worldwide, with 86 production units and fourteen Research and Development (R&D) centers in: Italy, France, Germany, Spain, Poland, the Czech Republic, Russia, Serbia, the Slovak Republic, Turkey, the United States, Mexico, Brazil, Argentina, China, Korea, Japan, India and Malaysia. (The sites of the Magneti Marelli plants are displayed in Figure 28.

Its current workforce numbers about 43.000. The company supplies the leading car makers in Europe, North and South America, and Asia.

Figure 28 - Magneti Marelli plant locations (Magneti Marelli S.p.a. , 2017).



The diversification of the Magneti Marelli portfolio is based on a vehicle's functional parts, generating subdivisions along the following business lines:

1. Electronic Systems Research: the development and production of instrument panels, displays, and infotainment and telematics solutions (instrument clusters; infotainment & telematics, lighting & body electronics).
2. Plastic Components and Modules: the design, development and production of complex systems made of plastic.
3. Automotive Lighting: there search, development and production of automotive lighting solutions.
4. Powertrain: the production of components for engines and transmissions for cars, motorcycles, and commercial vehicles.
5. Suspension Systems: the design and production of suspension modules and components and shock absorbers for a wide range of applications with a focus on weight reduction.
6. Exhaust Systems: the development and production of exhaust systems using advanced technologies in terms of performance and quality.
7. Motorsport: the research and development of electronic and electro-mechanical systems for two-wheeled and four-wheeled racing vehicles.
8. Aftermarket Parts and Services: spare parts, motorists' assistance services and training and technical know-how for the Independent Aftermarket.

4.2 TOWARDS SUSTAINABILITY

For Magneti Marelli sustainability constitutes a strategic approach to business with respect to the economic, social and environmental aspects of the territories in which the company operates: a business practice involving all corporate processes in accordance with the stakeholders' interests; a behaviour requiring long-term commitment and continuity; a voluntary commitment to go beyond what is required by law. For Magneti Marelli the concept of sustainability assumes the same importance as that of economic growth, product quality and technological innovation, to the extent that it has created within the company programmes aimed at implementing sustainability. In response to the ever-increasing global sustainability challenges, Magneti Marelli has applied new schemes at all levels of the organisation, in order to integrate the management of sustainability activities during company activities. The ultimate purpose is to share experiences and knowledge from the various Business Lines so as to become common assets on an international level. Following many years of hard work, the sustainability mindset has been established within the company at the various levels and departments (R&D, logistics, purchasing…). In the implementation of the concept of sustainability, Magneti Marelli's approach consists in the integration of three main fronts - the environment, society and the economy. With regard to its development, the company tries to find a balance between the economic, environmental and social dimensions. For Magneti Marelli, economic sustainability is based on its ability to remain financially solid, while balancing financial and ethical aspects. Environmental sustainability is based on the ability of the company to operate while respecting the natural heritage, understood as a limited resource, the use of which should not compromise the rights of future generations. Social sustainability is based on the ability of the company to operate in accordance with the needs of society and of local communities. The source of inspiration for the company is represented by the stakeholders' needs and expectations. Beginning with the requirements of clients and followed by the checking and selection of the suppliers, Magneti Marelli tries to adopt criteria of self-regulation which impact on its business model, on the organization and on company procedures, so combining results and responsibility. These regulations have enabled the Company to take on board FCA Sustainability: contributions to FCA achievements and performance through Magneti Marelli sustainability projects and activities (Dow Jones Sustainability Index, Great Place to Work Survey, LCA, Sustainable Supply Chain, and Gap Analysis ISO 26000, participation in Carbon Disclosure Project). Furthermore, sustainability as leverage represents a good marketing strategy, because it promotes customer values and Government expectations, (the publication of Start - MM Sustainability Magazine).

The integration of the company's aims with regard to sustainability takes place at two distinct levels: the corporate level and that of the product. Even though the principles regarding the development of sustainability are based on the same values, the methodology and the implementation are strictly conditioned by the object under investigation. In this sense, there are two different modes of operating, depending on whether the sustainability principles are applied at the corporate or product level.

4.2.1 SUSTAINABILITY AT CORPORATE LEVEL

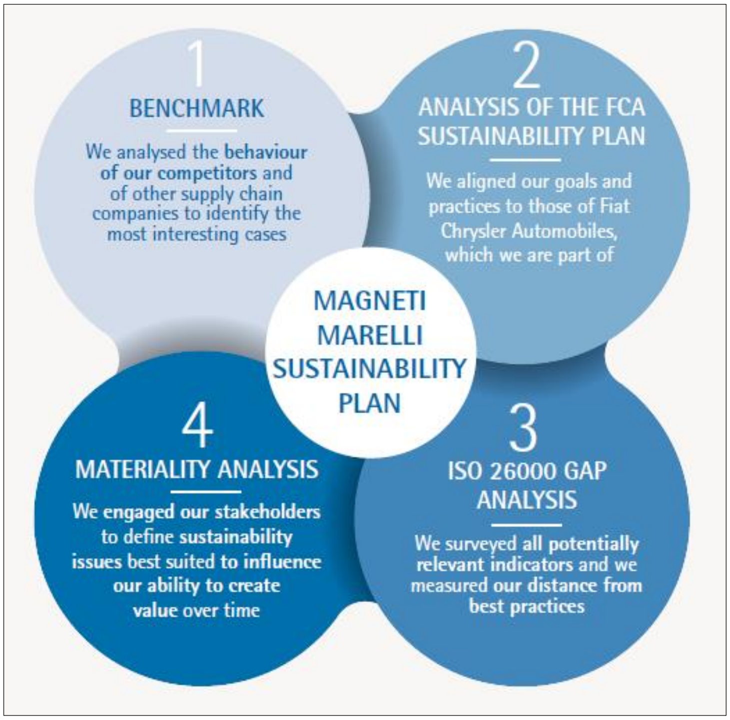
In order to achieve sustainability targets and consequent certifications, the company has started to apply several standardized procedures in the various plants. The actions undertaken have led to significant achievements and the granting of numerous international standards certifications: ISO 14001:2015, BS OHSAS 18001:2007 and ISO 50001:2011. Furthermore, Magneti Marelli has created its own customized Key Performance Indicators (KPI) in order to monitor its performance in a quantitative way, focusing on environmental and social aspects, aiming at gradual improvements. The measures taken concern: i) production and waste recycling ii) water consumption iii) emissions into the atmosphere and energy consumption. So far, Magneti Marelli has tried to build up its own sustainability system, based on various models and the standardization already existing in the global scenario. As part of the FCA group, Magneti Marelli produces reports on its sustainability performance in accordance with the FCA Group’s tools for sustainability: Code of Conduct, Sustainability Guidelines and Policy Report. Regarding the social criteria, Magneti Marelli follows the OHSAS 18001:2007 standard and, in general, applies the *Workplace Health and Safety Management System* to detail the basic requirements for ensuring the health and safety of its workers. Moreover, Magneti Marelli is committed to providing hours of training for its employees on Health and Safety topics. Training workshops, on the topic of sustainability, have taken place-involving professionals from different origins and backgrounds who have collaborated in the mapping activities of sustainability initiatives. In the application of its Quality Management System, the company follows the technical specifications of the ISO/TS 16949:2009 specifically customized for the automotive sector. In fact, this was developed by the International Automotive Task Force (IATF) and represents a mandatory requirement in relationships with major carmakers.

4.2.1.1 THE MAGNETI MARELLI SUSTAINABILITY PLAN

With the support of the Sustainability Committee and following the Sustainability Programme (Figure 29), the company carried out a preliminary analysis regarding the development of the Sustainability Plan. The Sustainability Plan in its development has followed two levels of operation: a practical one, which provides for the implementation of pilot projects and another at a more methodological level, which leads to the development of an evolving Plan designed to continually measure and evaluate the path taken, updating and redefining goals with a view to defining our best practices.

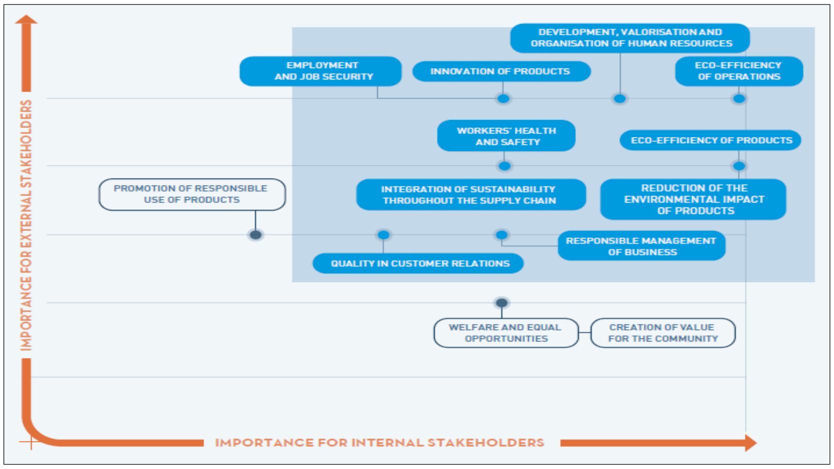
The road map is based on four steps, starting from the mapping of the indicators found in leading international guidelines and industry standards (GRI-G4 Global Reporting Initiative, ISO 26000, Global Compact). First, the contextualization of the indicators in relation to the Automotive sector, through a benchmarking process conducted on 16 Magneti Marelli peers, taking into consideration official sustainability tools and documents, which allow the identification of relevant indicators on which subsequent analyses are centered. Subsequently, the analysis of the specific industry scenario, public opinion and the pressures on Magneti Marelli on the one hand, provide evidence of political, economic and social phenomena able to impact Magneti Marelli's strategies and also help to identify critical issues for the company through the analysis of media and web press coverage. Lastly, the analysis of the code of conduct and company policies are analysed to provide the company's commitment to the values relating to internal management practices.

Figure 29 - Magneti Marelli sustainability plan.



An important theme is the engagement with the internal and external stakeholder. For the internal stakeholder this means the involvement of Business Area Managers who help define the relevance of sustainability indicators within the company, whereas for the external ones the focus is to give attention to the key stakeholders with whom we compare notes on key indicators, collecting ideas, insights and opinions. At this point the *materiality matrix* Figure 30 shows the important themes which have a relevant impact on the Company's activity with regard to the internal and external stakeholder's important issues scales.

Figure 30 – Magneti Marelli materiality matrix.



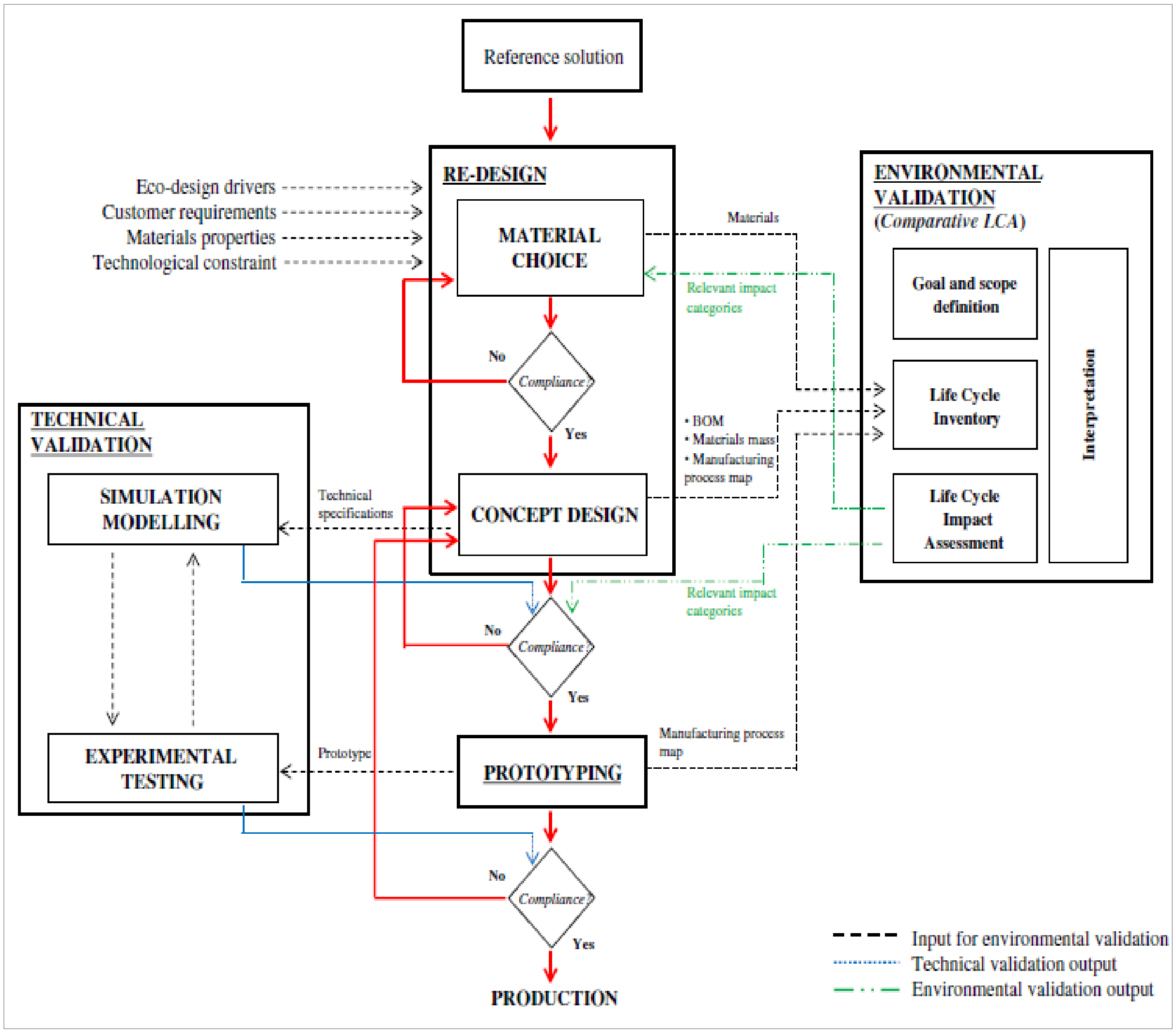
4.2.2 SUSTAINABILITY ACHIEVEMENTS AT PRODUCT LEVEL

The goals of sustainability development are monitored and applied at the macro level of the entire company, and are also integrated within the products. In fact, one of Magneti Marelli's main objectives is to develop intelligent solutions and systems that contribute to the evolution of mobility according to the following criteria: environmental sustainability and the safety and quality of life inside the vehicle. Magneti Marelli is committed to developing its product with the aim of reducing the impact caused by the effect of its production activities on the environment, in compliance with social values and costs optimization. Driven by these requirements, during the R&D stage the company makes every effort to minimize any environmental impact, depending on technical feasibility, thus harmonising performance characteristics and properties of eco-compatibility. Important projects have kicked off during the past year, such as the Life Cycle Assessment program of the product, the monitoring of the Supply Chain according to social and environmental criteria. Numerous actions have been undertaken that have resulted in the carrying out of Life Cycle Assessment analyses on a larger scale of products and the enhancement of sustainable mobility technologies (focusing on eco-efficiency and safety).Efforts have focused on technologies in the areas of powertrain, transmission and exhaust systems aiming at the reduction of fuel consumption and emissions, and also for dealing with the major problem of intelligent traffic management through info-telematic and intelligent navigation tools. Tangible examples (Magneti Marelli, 2018)of this are: KERS (the energy recovery system developed for F1 and now a source of technological spin-offs and other solutions for systems and components aimed at mass-produced hybrid and electric engines), TETRAFUEL® (the TetraFuel® system automatically chooses the fuel based on driving needs, optimizing the ratio of performance, fuel economy and low emission of exhaust gases), AMT (The Automated Manual Transmission is an automated mechanism of manual transmission which allows for the optimization of gear shifting, thereby reducing fuel consumptions and CO2 emissions), GDI (Gasoline Direct Injection) can considerably reduce the impact in terms of CO_2 emissions; specifically, GDI systems allow significant fuel savings. Thanks to telematics and network technologies, and to the integration of electronic systems found on a vehicle with central infrastructure and service providers, the automobile has become a part of an integrated and intelligent system that can improve quality on board the vehicle and on the road, as well as in the surrounding environment.

4.2.2.1 THE ROLE OF LCA IN THE R&D OF A PRODUCT

In order to promote vehicle sustainability performance, the model proposed here, which has consolidation potential, was developed and recently used within Magneti Marelli© as an innovative life-cycle design and development process for the specifications of a new product. In order to be most effective, the examination of the environmental impact takes place during the conceptual design stage; in fact, at this stage the environmental attributes of a product can be integrated. This novel approach was first used and implemented in the specifications of a new design for a powertrain throttle body (M. Delogu, 2018). The present R&D workflow (Figure 31) is structured as an interactive and iterative process and is made up of four main phases: *Re-design, Technical Validation, Environmental Validation and Prototyping*. The approach involves integrating the environmental impact analysis (performed in the *Environmental Validation* stage) in the traditional design procedure (*Re-design, Technical Validation and Prototyping*). In this manner, the technical requirements are combined with the environmental properties, thus providing a new decision–making formula in the final design approval. Environmental driver/s occur/s in the R*e-design* stage; in this way, the environmental aspect becomes a co-pilot driver helping to define the direction of future design decisions and assumes the same importance as the technical requirements for the product. Several re-design drivers, as a part of DfE principles, could therefore be selected in the choice of the environmental improvement strategy for the product. The *Re-design stage* is the most challenging one since the decision-makers have to find a balance between the following objectives') satisfying the customers' requirements, ii) producing a product in compliance with the functional and technical requirements, iii) improving the environmental performance of the product during its life cycle, iv) weighing up the economic expediency and thus harmonizing performance characteristics and properties of sustainability. The *Environmental Validation* is performed by means of comparative LCA, between reference and innovative design solutions for the given component. In this way, the LCA methodology is considered to be a validation technique providing useful feedback for the designers with regard to the best environmental impact scenario. The LCA is an instrument widely used by the automotive industry and car-makers to measure the environmental performance of their product (Balzer, 2015) so it could be supportive as an environmental management tool for product development in the engineering field. Through the LCA analysis it is possible to sketch a profile regarding the environmental impact on the selected categories (Life Cycle Impact Assessment stage), and thus obtain results that are measurable and monitorable. However, the design process is thought to be a top-down approach, where data among all the R&D players (designers, LCA expert, test engineering, project manager, calculation specialists…) are exchanged at different levels in a co-operative and iterative way. The purpose of the environmental analysis is to support the company in reaching sustainable goals and above all in making the design team and stakeholders more aware of the importance of their environmental role.

Figure 31 - Product R&D workflow combining DfE and LCA methodology (M. Delogu, 2018).



4.2.2.1 LCA PROJECTS IN MAGNETI MARELLI

Magneti Marelli activities on LCA studies began in 2012. By this time, the interest in this new methodology had grown to the final target of integrating the procedure in the R&D program, increasing knowledge in the environmental aspect of materials and technology. The result of these efforts have led to carrying out 12 projects, through the involvement of five business lines and the testing of innovative materials and technological variations, with the support of the various stakeholders.

For Magneti Marelli, the LCA is an important instrument that can be used, not only to supply environmental information for the improvement of product performance but also to comply with automotive environmental legislature and to promote the spread of green awareness.

Magneti Marelli has developed the LCA studies in accordance with the following guidelines:

a) Environmental management systems and environmental performance evaluation[(14001, 2015), (14004, 2016), (14031, 2013), (14032, 1999)];

b) Environmental labels and declarations [(14020, 2002), (14021, 2016), (14025, 2010)];

c) Integration of environmental aspects in product design and development (DfE) (14062, 2002);

d) Inclusion of environmental aspects in product standards (ISO Guide 64, 2008);

e) Environmental communication (14063, 2010);

f) Quantification, monitoring and reporting of emissions and removal, validation, verification and certification of GHG emissions [(14064-1, 2006), (14064-2, 2006), (14064-3, 2006)].

In general, for the automotive sector, the main environmental objective consists in the lightweighting of components as an ultimate strategy aimed at reducing two important issues: fuel consumption and GHG emissions. In fact, there is a correlation between a component's weight and these two factors. Other strategies are based on the inclusion and selection of renewable and/or recoverable materials. As the LCA encompasses all the materials and energy consumption throughout the component's life cycle, it is used to monitor where the greatest expenditure is generated and in this way identifies where efforts at reductions should be concentrated. The LCA analysis is performed by comparing the condition of components having an equivalent functional performance. So, the analysis is aimed at identifying design and technological alternatives which, based on the same functional performance, present the most/less environmental impact profile.

5. LIFE CYCLE SUSTAINABILITY ASSESSMENT PROJECTS IN MAGNETI MARELLI

> *You never change things by fighting the existing reality.*
> *To change something, build a new model that makes the*
> *existing model obsolete."*
> *(Buckminster Fuller)*

> *"I think it is interesting to see this holistic view on car*
> *development. Incorporating the several pillars of*
> *sustainability idea at the engineering level in my view is*
> *a worthwhile and very fruitful concept".*
> *(Dominik Jasinski, James Meredith, Kerry Kirwan)*

Following four years' experience of LCA studies, in 2016 the company extended the scope of LCA analysis, integrating the remaining two sustainability pillars as a part of the product Sustainability Life Cycle Assessment (S-LCA), thus including the Environmental Life Cycle Cost (eLCC) and the Social Life Cycle Assessment (SLCA).Life cycle assessment (LCA) has led to the widespread concept within Magneti Marelli, for assessing the environmental impact of its products, so as to support decision-making in the implementation of a sustainability policy. Recommendations based on LCA, however, concern only the environmental aspects; in order to implement an integrated sustainability policy, economic and social dimensions have to be included so as to make equal trade-offs throughout the product life cycle, in accordance with LCSA analysis purposes. LCC considers economic implications in a life cycle perspective, while S-LCA is currently the only social assessment method that takes into account social aspects from a life-cycle perspective. The following section presents a summary of methods for assessing the environmental, economic, and social impacts of Magneti Marelli© products, but could be applied at a more general level in assessing automotive products.

5.2 MATERIALS AND METHODS

The characteristics shared by all three methods are respectively: i) the product life cycle perspective, ii) the unit of assessment, which is the product function (functional unit) and iii) the quantitative outcomes. The methodology carried out considers the full life-cycle, so that all the product cycle phases are taken into account in view of the "cradle to grave" approach. The LCA is applied according to the framework drawn from the ISO 14040 and 14044 standards but, since there is no standardized method providing official guidance regarding the application of LCC, several examples of LCC case studies have been adapted as models. LCC has never been explicitly developed into a broad and generally applicable methodology. The references used as an inspiration to development the LCC method within the MM context are: the Code of Practice on Environmental Life Cycle Costing (Swarr et al., 2011)and the publication of (Hunkeler et al., 2008). Instead, the method for assessing the social impacts of a product follows the UNEP/SETAC guidelines and the following Methodological Sheets (UNEP/SETAC 2013), based on the Roundtable for Product Social Metrics initiatives. In order to increase comparability and ultimately compatibility between the three methodologies, the framework drawn from the ISO standards for LCA has been adapted as a model and followed insofar as it has proved to be practical and meaningful. Only LCA, like eLCC, has been developed according to a "cradle to grave approach". Considering the nature of the object of the analysis for SLCA all the phases beyond the "gate to gate" perimeter have been excluded. In fact, from a social point of view components cannot be considered directly responsible for the social impact of the use phase (i.e. vehicle breakdown…). The social impact assessment of the use phase would only make sense if the user would be directly influenced by the component operation. On the contrary, the vehicle/component use is considered significant in the LCA and LCC, since the fuel consumption and its cost are related to the component for its mass; therefore, it is reasonable to allocate the environmental and economic burdens to the component. The LCSA system boundary of a generic component is depicted in Figure 32, whereas the actors involved in the whole supply chain are presented in Figure 33.

Figure 32 – LCSA methodology perimeter of the analysis.

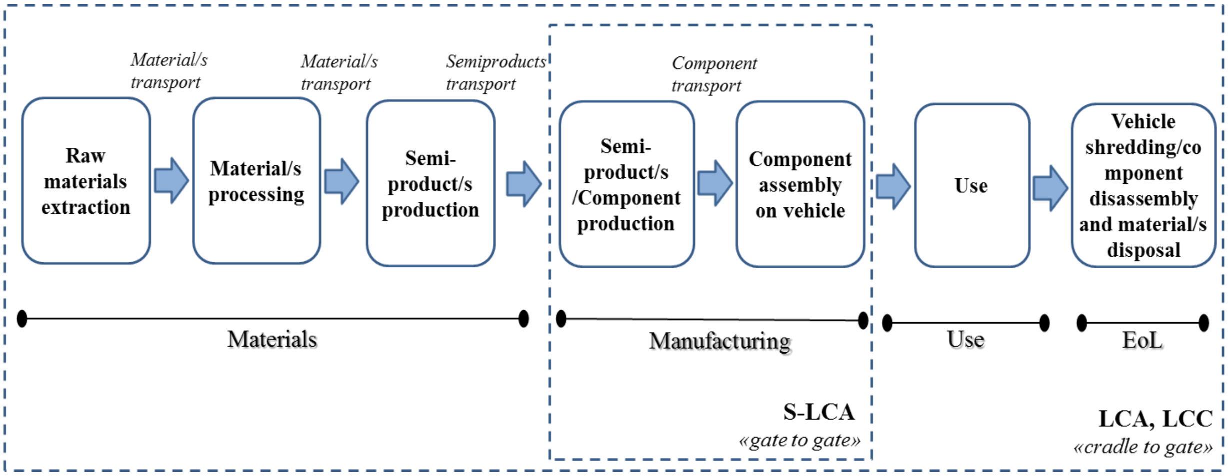
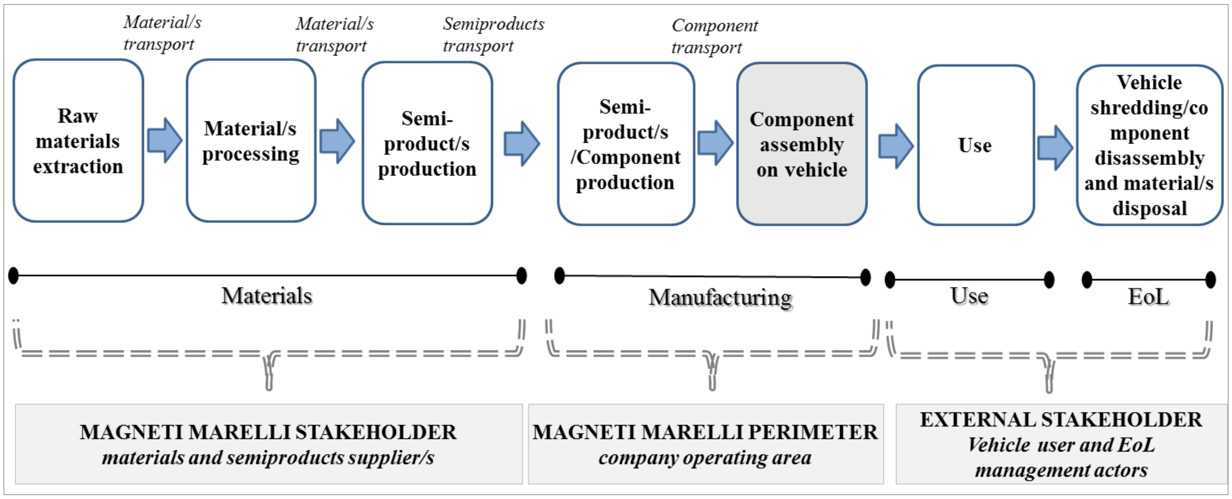


Figure 33 – Actors involved with product system boundary.



Data quality includes information about data used in the study such as time-related coverage, geographical coverage, precision, etc. Moreover, the source of data is another fundamental aspect.

Data for material production and manufacturing should reflect the current state of the art and be geographically representative. Overall, three types of data can be distinguished: i) *primary data* (e.g. direct data, measurements) ii) *secondary data* (database, literature, GaBi database) and *assumptions*.

5.1.1 LCA METHODOLOGY IN MAGNETI MARELLI

In the following paragraph are described the principle guidelines adopted for the implementation of LCA analysis for a generic MM component. The components' life cycle modelling has been implemented within Gabi software[32] [6.115 DB].

5.1.1.1 LCA DATA INVENTORY LCI

As previously mentioned, the purpose of LCA is to address the environmental impact of a product over its life cycle stages. Consequently, in accounting for all the relevant input and output flows during all the processes involved, the full life cycle of the product has been considered. Considering a generic automotive product, its main life cycle stages could be grouped as depicted in Figure 22meaning for:

- materials which include extraction of raw materials extraction and their processing, and semi-products produced by MM suppliers;
- manufacturing accounts for all the processes involved within the MM perimeter to produce the component, starting from the materials and or semi-products, to the final stage of assembly within the vehicle system;

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[32] http://www.gabi-software.com/international/software/

- transport assesses the impact attributed to the shipments for all the life cycle phases in-between;
- use is based on component operation within the reference vehicle selected for a specific life time mileage, which is at minimum 150,000 km;
- end of life: consists of all the processes involved to recover/dispose of the materials (for dismissed vehicles) according to their typology.

Below is also discussed the modality of a generic data collection modality, with further details regarding each product analysis dealt with in the following chapter 6. Wherever possible, process parameters (materials and energy flows) were obtained from direct measurements and/or estimationson industrial processes; in other cases results from GaBi database [6.115 DB] processes were used. According to ISO 14044, all the processes and materials related to primary data (database sources), are allocated using mass/energy reference values.

MATERIALS

The materials category includes the impact originating from the extraction and production of the material. The production of a material refers to its final state before entering the MM manufacturing plant, with regard to its form: coil, slab, ingot, flat, sheet, granular etc.… Moreover, the materials stage takes into account the production of all the semi-products produced beyond the MM perimeter. For the production of its components, MM employs a wide array of materials, which differ both in their form and in composition. The activities of experimentation are increasingly projected towards the use of reinforced plastic materials; most of these are innovative materials, whose production process is strictly confidential. Despite this fact, suppliers have responded positively to the request for manufacturing data sharing. This possibility has allowed the company to model various customized material profiles (Table 2), and thus obtain more reliable profiles than those found in the usual software databases. All the materials profile and modeling are strictly dependent on the process in question and on the information shared by suppliers. Whenever it was not possible to get primary data, the Gabi software DB and Ecoinvent DB were used. All of the novel materials profiles, modelled within Gabi software, are shown in ANNEX B.

Table 2 - List of all the materials modeled within Gabi software.

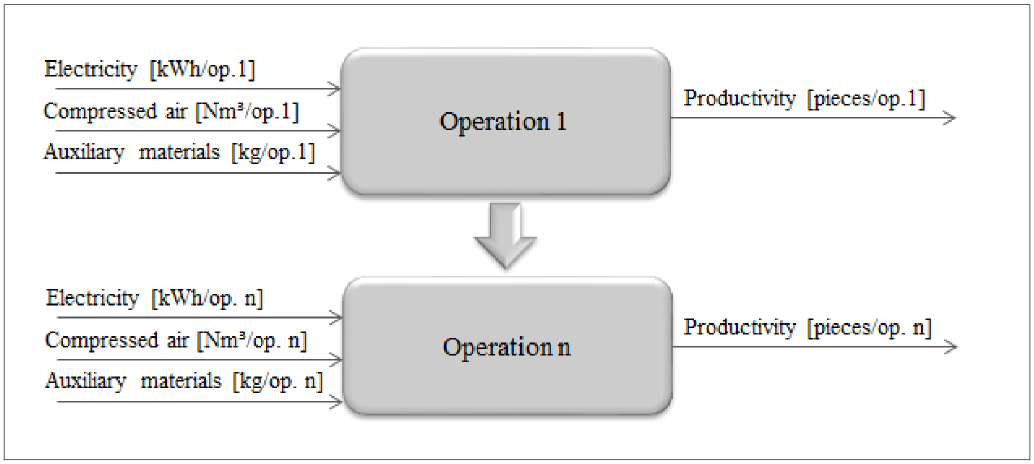
	Name [typology, form, production process]	**Specification**
Metals	Stainless steel 441 *[flat production]*	Ferritic stainless steel in form ofsheet flat-rolled metal
	Stainless steel 441 *[cold rolled coil]*	Ferritic stainless steel in form ofcold coil-rolled metal
	Stainless steel 301 *[stamping and bending]*	Austenitic stainlesssteelplaced in blank into a stamping press and bended
Non-metals	Aluminium AlSi13Cu *[die-casting]*	Secondary aluminium alloy die-casted [from ingot form]
	Aluminium AlSi13Fe *[ingot]*	Secondary aluminium alloy in form of ingot
Plastic and composite	PPS-GF40 *[granular]*	Polyphenylene sulphide reinforced with 40 percentage of glass fibres in granular form
	PA66-15CF-10GF *[granular]*	Polyamide 66 reinforced with 15% of carbon fibres and 10% of glass fibre in granular form
	PA6-GF60*[granular]*	Polyamide 6 reinforced with 60% of glass fibre in granular form
	PBT-GF30 *[granular]*	Polybutylene terephthalate reinforced with 30% of glass fibre in granular form
	PET-GF50 *[granular]*	Polyethylene terephthalatereinforced with 50% of glass fibre in granular form
	PP-GF30 *[granular]*	Polypropylene reinforced with 30% of glass fibre in granular form
	PP-NF45 *[granular]*	Polypropylene reinforced with 45% of woodchip in granular form
	PP-23HGM *[granular]*	Polypropylene reinforced with 23% of hollow glass microspheres in granular form

MANUFACTURING

The manufacturing phase accounts for all the energy consumption and all the auxiliary materials involved in the production of the component. Only the operations that take place within the MM production perimeter are considered in this phase. Starting from the process flowchart, all the consumption relating to the operations involved is traced. The classification of all the consumption is based on the typology of each flow, whether electricity, compressed air, auxiliary materials and so on. A general scheme relating to this procedure is shown in Figure 34. In the present illustration there is no reference to the outcome of scraps since their control is stringently dependent upon processes and material features. Occasionally scraps are recovered and figure as avoided income materials and are not counted; instead scraps are accounted as process waste.

In the calculation of compressed air consumption, different typologies of machinery have been considered, according to power consumption, system efficiency and air blow distributed. The compressed air system used in MM plants could be grouped as follows: i) high/low power consumption; 7 bar; low/high efficiency; high/low power consumption; 10 bar; low/high efficiency; high/low power consumption; 14 bar; low/high efficiency. In order to calculate the consumption related to the functional unit [FU], each individual input flow is divided by the referred productivity according to Formula 1.

Figure 34 – General production process flowchart with input and output reference for manufacturing.



Formula (1) $Incidence/FU = \frac{Referenceinputflow}{Productivity}$

TRANSPORT

The logistics phase takes into account all the route phases in between the single life stages, starting from the delivery of materials to the final step of product assembly within the vehicle system. The means of transport considered are those of reference within the data set of Gabi software. For the application of the case studies the means of transport are truck trailers and ocean ship containers, considering the selection of the free parameters which are strictly dependent upon the specific case study. The means of transport with reference to the specific free parameters are shown in Table 3. To calculate the distance travelled, the web map-routing services of Google Maps® programs have been used.

Table 3 – Means of transport to model logistic routes.

Means of transport	Free parameter
Truck-trailer	distance travelled [km]; fuel typology; gross weight; payload capacity
Ocean ship container	distance travelled [km]; fuel typology; payload capacity

USE

The use stage covers the operation of the vehicle equipped with the reference component. It expresses the consequence of the consumption of energy (in the form of fuel or electricity) and of all the products necessary for operation. The impact is calculated according to life expectancy, expressed in units of measurement consistent with the typical use of the product, and depends on the modalities with which the mission is carried out, according to cycles of use arising from regulations specific to the sector. For all the components the minimum vehicle life span is fixed at 150,000 km, during which it is assumed that the component does not require exchange or maintenance. The principal flows taken into account are the fuel/electricity consumption for vehicle operation and the exhaust pipe emissions. All of these flows are assumed to directly depend upon vehicle mass and therefore component mass incidence on the entire vehicle mass weight. Thus, to calculate the environmental impact attributable to the component operation, the analytic model proposed by (Köffler and Rohde-Brandeburger, 2009)was used, which scales the fuel consumption as directly dependent on the mass of the component (mass induced-fuel consumption factor). The calculation of the fuel consumed is based on the mass-induced fuel consumption starting from:

– The amount of work necessary to move 100 kg on a specific driving cycle;

– The differential efficiency of the internal combustion engine.

Mass of fuel consumption (m_{fuel}) is calculated through the following equation(2):

$$m_{fuel} = m_c \times f_m \times d_m \qquad (2)$$

in which:

- m_{fuel} = represents the fuel consumption during the entire vehicle's life-time attributable to the reference component ;
- m_c = mass of the reference component;
- f_m = is the mass-induced fuel consumption for a normally aspirated gasoline car through the New European Driving Cycle (NEDC).

The amounts of emissions [CO2 and SO2] during the entire vehicle's lifetime attributable to the mass of the component are calculated using the following equation (3) and (4):

Formula (3) $\text{emissions}_{CO2} = m_{fuel} * f_{CO2}$;

Formula (4) $\text{emissions}_{SO2} = 2 * m_{fuel} * f_{SO2}$;

- emissions_{CO2}= emissions of CO_2 pollutant during the entire vehicle life-time attributable to the component mass weight (kg);
- m_{fuel} =represents the fuel consumption during the entire vehicle life-time attributable to the brake pedal ;
- f_{CO2} = CO_2 emissions generated during the consumption of 1 kg of fuel [kg CO_2/Kg fuel];
- emissions_{SO2} = emissions of SO_2 pollutant during the entire vehicle life-time attributable to the component mass weight (kg);
- f_{SO2} = SO_2 emissions generated during the consumption of 1 kg of fuel [kg SO_2/Kg fuel].

As the model scales the emissions linearly with the fuel consumption attributable to the component, only the usage emissions, which directly depend on the amount of fuel consumption CO_2, are considered. To modelthe use phase of a component, the same technical parameter of the car on which the component is installed has been selected and is shown in Table 4.

Table 4- Parameters used for the modeling of use within vehicle X.

	Parameter	**Value**
Vehicle's technical charateristics	Model [powertrain, weight, emission stage]	Depends on vehicle
	Mixed consumption [l/100km]	Depends on vehicle
	Motorway per-km CO_2 emission [g/km]	Depends on vehicle
Operation	Vehicle life time [km] -**dm**	150,000
Analytic model [NEDC]	Mass induced fuel consumption [l/100km*100kg] - FRV_PMR [Gasoline] - **fm**	0.15
	Mass induced fuel consumption [l/100km*100kg] - FRV_PMR [diesel] - **fm**	0.12
Fuel density	Gasoline [kg/dm³]	0.74
	Diesel [kg/dm³]	0.84
Specific consumption [kg/kg fuel]	CO_2 emissions generated during the consumption of 1 kg of fuel [kg CO_2/Kg fuel] – $\mathbf{f_{CO2}}$	3.12
	SO_2 emissions generated during the consumption of 1 kg of fuel [kg SO_2/Kg fuel] - $\mathbf{f_{SO2}}$	0.00015

END OF LIFE

The following section deals with the final stage of the life cycle of the product, which is not directly managed by the company. Nevertheless, the company can give an important contribution in this field by selecting materials which could be recycled and/or recovered (design for end-of-life), or design components which are easily dismantled from vehicles (design for disassembly) before the final shredding and/or by the adoption of specific techniques which allow the re-use of the product itself. First of all, the principle directives relating to the management of vehicles at the end of their life "End-of-life Vehicles" ELV are described. Subsequently, the framework adopted by the company to model the EoL scenarios of its products is discussed in depth.

Regulation

The Directive 2000/53/EC, provides guidelines on the ELV waste management within the European Community. The regulation promotes the reduction of hazardous waste, starting from the component design to the final recovery of material at the end-of-life stage. The waste management includes the collection and differentiation of materials through mechanical, chemical and physical selection, with the possibility of recovering plastic parts to generate energy, preferably in schemes of thermal and electrical cogeneration and finally, the long-term securing of the fractions and their disposal in controlled landfills. The purpose of this type of regulatory provisions is to achieve higher levels of recovery of materials and to limit the waste of natural resources. With the implementation of the European directive on End-of-Life vehicles and 2005/64/EC on the type-approval of motor vehicles with regard to their reusability, recyclability and recoverability, car manufacturers are obliged, as part of the car type-approval, to meet a recycling rate of at least 85% and a recovery rate of 95%. The remaining 20–25% is referred to as automotive shredder residue (ASR), which is largely disposed of in landfills due to its heterogeneous and complex matrix, or else undergoes an incineration (see Table 5) process for energy recovery. Generally, End-of-Life Vehicles (ELV) are processed following the ISO 22628:2002 directive, according to a treatment scheme comprising three main phases depicted in Table 5. The purpose of this classification is to evaluate the potential of each material/part for its reusability, recoverability, recyclability or disposability.

Table 5 - EoL procedure flowchart of general vehicle (ISO 22626:2002).

Calculation steps	Vehicle elements		Assumptions
	General character	List	
1) Pre-treatments	Component parts and fluids	All fluids; Batteries; Oil filters; LGP tanks; CNG tank; Tyres; Catalytic converters	Reusable,recyclable or both
2) Dismantling	Component parts	As declared by vehicle manufacturer	Reusable,recyclable or both
3) Metal separation	Materials	Metals (ferrous and non-ferrous)	Recyclable
4) Non-metallic residue treatments	Materials	Glass	Recyclable
		Polymers (excludingelastomers)	Recyclable,recoverable or both[33]
		MONM	Recyclablerecoverable or both[b]
		Others	b

Overall, four main steps can be distinguished as follows:

1. *pre-treatment:*this is the first step, aimed at removing all dangerous substances (fuel, refrigerant liquids, batteries…);
2. *dismantling*: in which all the possible components are removed from the vehicle and properly sorted for specific reuse or recycling;
3. *separation of metals*: in this step all the remaining parts are shredded to reduce the overall volume with further separation of metals and the recovery of metallic fractions;
4. *non-metallic residue treatment:* in this phase the residue, ASR or fluff is collected and further processed depending on its inner components.

In order to provide feedback on the conduct of materials at the end of life (scrap) stage, the present model has been used to simulate the various scenarios based on ELV directives and industrial management operations. The model consists in the abstract representation of a real system, implemented after selecting the characteristics to be inserted. This sorting must be carried out with the aim of adapting the complexity of the model to the needs of the analysis. The level of detail allows an acceptable compromise between the reliability of the results and the opportunity of being implemented.

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[33] The apportionment among the three treatment possibilities is as declared by vehicle manufacturer

The implementation of the ELV model is far from simple. There are many decisional variables at stake, for which the results can vary considerably. One critical aspect is the balance of the material flows considering the allocation due to the possible credit arising from the recycled parts. Another issue derives from the selection of energy source credit, generated by the incineration process. The mix of the metals recovered is extremely heterogeneous and so it is not simple to get a good selection of the materials. In addition, the more the material is recycled, the worse its quality becomes (down-cycling issue), so a small addition of virgin material has to be considered. Whenever there is reuse, recycling or energy recovery, we need to ask who should get the credit and impact of recovery, whether the component in question is connected to either the upstream or downstream product system.

In our model, it is assumed that the component has not been dismantled, so it is therefore shredded inside the vehicle, and materials are subsequently separated and fed to the respective recycling/disposal routes/lines, according to the workflow depicted in Figure 35. The present flow chart reflects the management status of an ELV plant located in Italy.

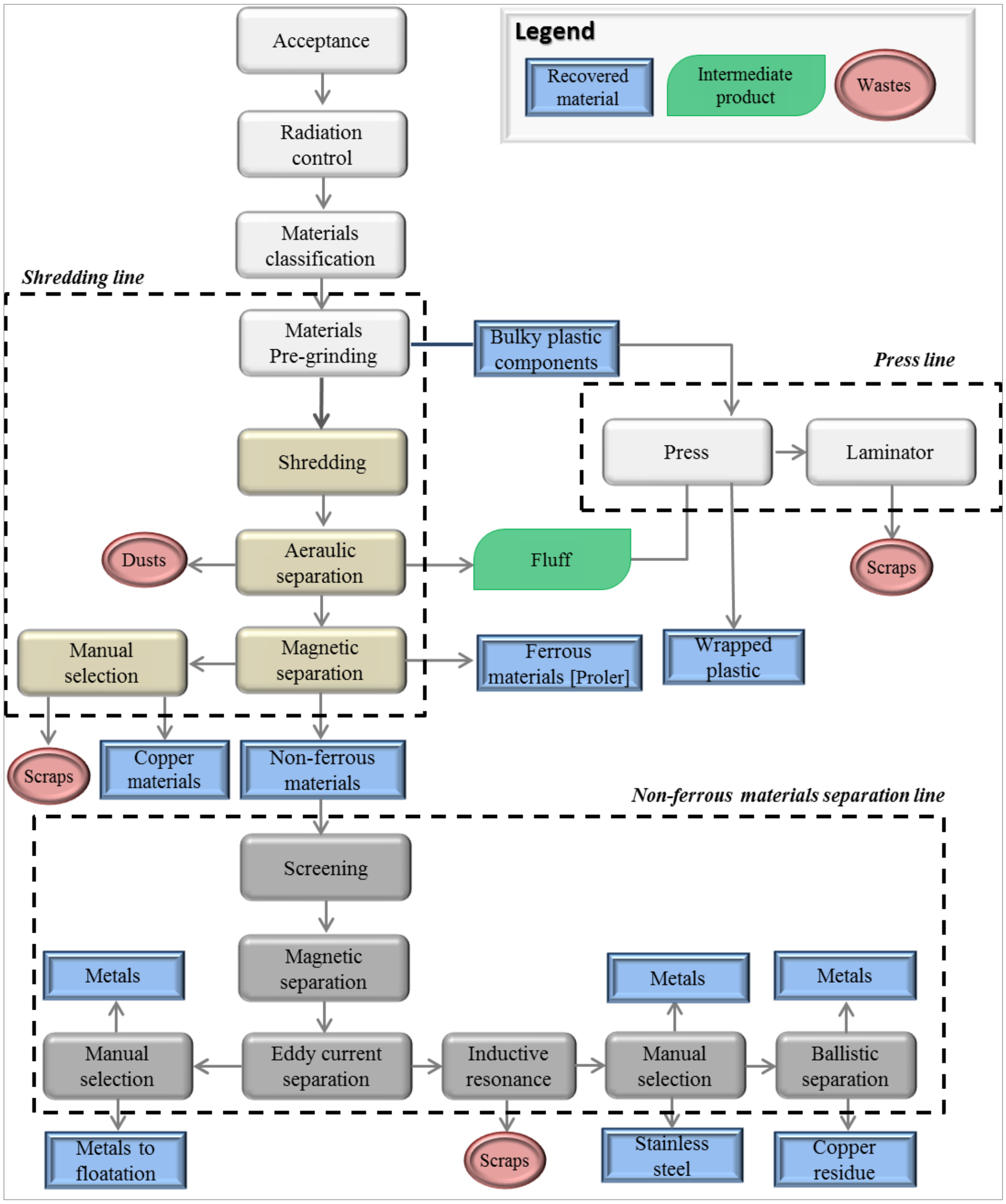
The plant consists of several production lines: i) the shredding line for the recovery of ferrous materials *(proler)* ii) the press line to compact the plastic parts *(fluff)* generated from the shredding line and iii) the non-ferrous materials line to recover the remaining materials (aluminium, copper and so on…).

The first line is dedicated to the processing of ferrous materials and essentially consists of a process of storage and classification, common to other lines, a phase of pre-grounding, a feeding belt allowing for the adjustment of the inflow to the mill crusher, an aeraulic separation system, a magnetic separation system and finally a cabin sorting. A first classification of the input material is defined on the basis of its ferromagnetic properties. Non-ferrous scrap constitutes only a small percentage of the total of the treated scrap. The wreck (machine drained and pressed - Figure 36, a) at the start is very heterogeneous, as it consists of different materials in terms of type, weight, volume, density and shape. The vehicle wrecks are inserted into the ferrous materials treatment line by an industrial loader (Figure 36, b).

The magnetic separator of the first line separates the non-ferrous metals that are destined for subsequent enhancement work in order to conclude their recovery at the non-ferrous recovery line plants, for recovery of materials such as: aluminium, copper, brass, electronics, glass and others (Figure 36, d).

The plant for the separation of the residue of lighter crushing, called Light-fluff or Car Fluff, is classified by the CER code 19:10:04; this contains plastics, padding, rubber, glass, fabrics and gaskets separated by suction and disposed of directly, as it is poor in recoverable metallic material (Figure 36, e).

Figure 35 - End-of-life flowchart for a non pre-dismantle automotive component.



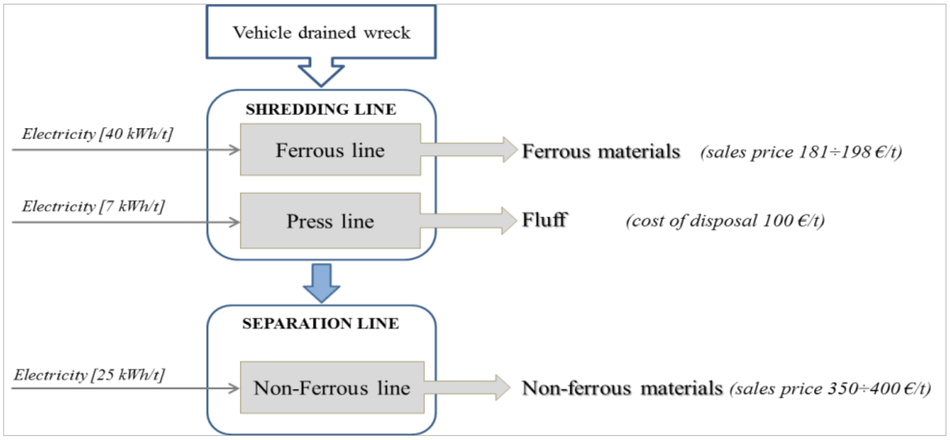
The shredding process is modelled by means of its energy consumption according to the weight of the composition of the brake pedal's materials. Following the flowchart in Figure 35 three EoL management options are modeled according to the composition of the materials for recovery:

- *Ferrous materials*: from wrecks → shredding → aeraulic separation → magnetic separation.
- *Plastics*: from recovery process of ferrous materials → fluff treatment in press machine.
- *Non*-ferrous materials: from recovery process of ferrous materials → screening → magnetic separation → eddy current → (optional: inductive resonance → ballistic separation).

Figure 36 – ELV plant a) car wrecks, b) wrecks input ferrous separation line, c) ferrous materials recovered after processing, d) non-ferrous materials after processing and e) car-fluff disposal after processing,

The energy consumption calculation is based on the mass of the materials to be treated according to the EoL options (Figure 37).

Figure 37 – Energy and cost flow for materials recovery/disposal at EoL stage.



In the ELV modeling, two scenarios are generally hypothesized: the first includes the environmental burdens of the recycling processes and grants credit for the recycled/ recovered materials (best option) and the second, in which all the materials are sent to the scrapyard and no re-allocation is considered (worst option).

To this end the *Avoided burden approach* methods[34] have been selected to model materials credit when the scenario selected is expected to recover/dispose of materials/energy. In the *Avoided burden approach*, the end-of-life scraps are recycled and offset demand for an equivalent quantity of virgin material (supposing no changes in the material functional properties). Scrap inputs to the product system are assigned an upstream burden of primary production which equals the credit that the previous product system would receive. If the product system is a net consumer of scraps then the upstream burden overcorrects the EoL credit.

5.1.1.2 LCA – LIFE CYCLE IMPACT ASSESSMENT [LCIA]

In this section life-cycle environmental impact has been calculated on the basis of data gathered during the inventory; it has been done by applying Classification and Characterisation to LCI data according to ISO 14040 standard guidelines. The results of Life Cycle Impact Assessment are reported according to CML 2001 Apr. 2015 regulations which classify the results of LCA studies by the following impact categories: i) Abiotic Depletion Potential (ADP); ii) Acidification Potential (AP); iii) Eutrophication Potential (EP); iv) Fresh Water Aquatic Eco-toxicity Potential (FETP); v) Global Warming Potential (GWP); vi) Human Toxicity Potential (HTP); vii) Marine Aquatic Eco-toxicity Potential (METP); viii) Ozone layer Depletion Potential (ODP); ix) Photochemical Ozone Creation Potential (POCP); x) Terrestrial Eco-toxicity Potential (TETP).

Additionally, the Primary Energy Demand [PED] (category from renewable and non-renewable resources [gross cal. Value]) has been considered as well as Resource Depletion Water, midpoint v.109. Additional information regarding the description of the impact indicators, as well as for the calculation method, are reported in ANNEX D.

5.1.2 LCC METHODOLOGY IN MAGNETI MARELLI

The method adopted is the *environmental LCC (eLCC)*,thus expanding the conventional LCC, usually focused on the costs for individual companies.Besides the existence of sector specific literature concerning eLCC application and the internal experience upon economic evaluation during component design, the identification of clear and comprehensive cost categories, and their related formulation, is still an aspect which needs to be developed and tested by means of applications and strictly depend on the company's decision-makers.

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[34] http://www.gabi-software.com/uploads/media/Webinar_End_of_Life_Oct2014.pdf

5.1.2.1 eLCC DATA COLLECTION LCI

In order to be consistent with the system boundaries and assumptions of the LCA, the following formulation (5) has been proposed:

Formula (5): $eLCC = C_{production\ (materials+manufacturing)} + C_{transport} + C_{Use} + C_{End-of-Life}$

More information about data collection and the calculation of such costs are reported in the following paragraphs. The perspective taken into account for the calculation of costs is that of MM, thus considering the cost of production which includes the cost of acquisition of materials and semiproducts with the addition of the cost directly attributed to the production of the component (direct cost). The perspective used in the analysis is mainly to 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. According to ISO 14044, all the processes and materials related to primary data (database sources), are allocated using mass/energy reference values. In the calculation of costs attributed to each life cycle stage, data from LCA inventory has been used and multiplied by the specific unit cost of the reference flow.

PRODUCTION

The production cost stage, accounts for the costs arising from MM external acquisitions (i.e. materials, auxiliary materials, semiproducts, equipments) and costs derived from the MM plant during the manufacturing phase (i.e. energy consumption, labour costs, maintenance costs…). In the calculation of production costs, various cost incomes should be considered, which are strictly dependent on the product system assessed and on the typology of the plant considered. Consequently, there is no single way through which production costs are calculated. Other factors which make it difficult to form a standard calculation scheme, are the plant management operation activities (whether or not the costs of auxiliary facilities, overheads, the heterogeneity of machines and their operation should be considered). Moreover the cost of materials and/ or semi-products strictly depends on the supplier's policy and if they accord with the MM company (purchasing policy, numbers of slots and frequency, slots quantity, shipments, equipment, labour). Due to the numerous variables which may come into play, a high degree of inaccuracy in the assessment still remains. Therefore, in this dissertation the production cost items vary from one case study to another. The only cost items which are constant relate to energy consumption, mainly electricity and compressed air, although it is difficult to attribute pricing to the electricity expenditure, since it varies widely from the place to place. However, with regard to the cost attributed to the blowing of compressed air consumed, the following assumptions have been taken into account. MM plants dispose of various degrees of systems which depends on a wide range of factors: i) working pressure ii) leakage level, iii) air demand profile / operating hours iv) type of compressors v) level of air treatment vi) distribution system sizing….

However for electricity and compressed air, the unit costs have been assumed to be constant and are reported in Table 6.

Table 6 - Average pricing for electricity and compressed air.

Life cycle phase	Flow	Unit cost	Source
Production (Manufacturing)	Electricity	0.12 €/kWh	*Eurostat 2018*[35]
	Compressed air	0.016 €/Nm³	*Silvent, 2016*[36]

LOGISTICS

In the calculation of the costs related to the transport stage, only the kilometres travelled were considered as a cost item, hence excluding any hypothesis of vehicle breakdown. As a whole, the cost calculation attributed to the transport phase takes into account the fuel consumption and the driver workforce. The economic cost element, allocated per km of *transport route for MM, is 1.1 €/km*. The general formula used to calculate the transport of one single item is according to the following equation (6) in which:

$$Ctransport = Tx\left(\frac{Q}{1000}\right)x\left(\frac{c}{G}\right) \tag{6}$$

- T: total distance travelled (km);
- Q: item weight (kg);
- G: truck gross weight (ton);
- c: cost per 1 km (constant = 1.1 €/km).

USE

The costs accounted in the use stage are attributed to the fuel expenditure and to externalities generated from CO_2 emissions, assuming there is no cost for vehicle breakdown and maintenance. Regarding the environmental eLCC, the total cost is attributed from the conventional LCC with the addition of the costs derived from the CO2 emissions generated during vehicle use and the resulting damage [€/kg emissions]. In the eLCC cost analysis for fuel consumption, two calculation methods have been considered and

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[35] http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics

[36] *https://knowledge.silvent.com/en/how-to-calculate-your-operating-cost-for-blowing-with-compressed-air*

compared. The first does not consider discounting (according to formula 7) and the second considers discounting[37] according to formula 8.Cost of air-pollutant damages were estimated, based on:

- ✓ Estimated emissions (g/km) both from vehicle operations and all fuel supply activities upstream of the vehicle and
- ✓ Estimated damage costs (€/g) of CO_2 emitted pollutants (Odgen et al., 2004).

Valuations of specific environmental damage costs are provided by the Clean Vehicles Directive 2009/33/EC (EC, 2016). CO_2 emissions were already calculated from the LCA analysis. Costs item parameters used to quantify costs during use stage are reported in Table 7.

Table 7 – Parameter used for costs calculation of use phase.

Flow	Unit cost
Fuel quantity (F)	Variable (kg)
Gasoline (G)	Constant 1.46 €/litre(Eurostat, 2018)
Diesel (D)	Constant1.26 €/litre(Eurostat, 2018)
CO_2 emissions cost	Constant4.00 x 10^{-5} €/gCO_2(EC, 2016)
Ct	net cash inflow during the period t
Co	total initial investment costs
r	discounting rate
t	number of time periods

$$C\textit{(without discounting)} = \text{Cost of fuel x Fuel quantity} \quad (7)$$

$$NPV = \sum_{t=1}^{T} \frac{C\,t}{(1+r)^{t}} - Co \quad (8)$$

END-OF-LIFE

In the calculation of the costs attributed to the EoL phase, it is necessary to take into account the reference scheme with the treatment processing for the recovery and separation of a specific material typology. Overall, according to Figure 37, three different typologies of materials can be distinguished: metals, non-metals and fluff. Indeed the costs attributed to the recovery/and or separation of the

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[37] Using Net Present Value (NPV)

aforementioned materials strictly depend on the amount of electricity consumed, as expressed in Table 8. In addition, another aspect should be taken into account since, once recovered, ferrous and non-ferrous materials are sold. Therefore, the EoL processing considers the sale price as an income. On the contrary, fluff materials cannot be sold and an additional cost for their disposal is expected. The price of materials either sold or disposed of, is dependent on the quality of the process yield. To sum up, the following range is considered for the following materials: i) ferrous materials: sale price estimated at 181÷ 198 €/t ii) non-ferrous materials: sale price estimated at 350÷ 400 €/t and iii) fluff: cost of disposal estimated at roughly 100 €/t.

Table 8 – Unit cost for materials recovery from car wrecks.

Life cycle phase	Flow	Unit cost	Source
End of Life	Shredding line to recover ferrous materials	0.04 kWh/kg	*Primary data*
	Press line to recover fluff	0.007 kWh/kg	*Primary data*
	Separation line to recover non-ferrous materials	0.025 kWh/kg	*Primary data*

5.1.3 S-LCA METHODOLOGY IN MAGNETI MARELLI

The S-LCA analysis could enhance the social performance of the companies concerned by helping them to build a targeted strategy for the future development of social policies. Moreover, the social analysis can be considered a valuable tool to support the decision-making process involving different stakeholders with different knowledge and background and could help in managing social risk, thanks to the identification of the social hotspots. The final aim of the social approach is to collect social information through social KPI's. S-LCA goes further by making it possible to quantify and qualify their performance, providing a structured and robust framework. In the following section are described the general guidelines adopted in the execution of the social impact assessment analysis, with a further description reported in ANNEX E. The framework considered is the one proposed by the Handbook. The perimeter of the analysis is limited to the MM manufacturing plant.

5.1.3.1 S-LCA DATA COLLECTION

The data inventory has been developed according to the quantitative approach, proposed in the Handbook for Product Social Impact Assessment. The data inventory includes three main steps:

1) Collection.

2) Allocation to FU.

3) Aggregation.

COLLECTION

Data collection regards groups of stakeholders of “workers” and “local communities” Table 9), using a quantitative assessment method. The quantitative indicators attributed to the social topic could be in two forms: absolute numbers (i.e. number of actions) or percentages (i.e. the percentage of workers).

Table 9 - List of stakeholders and social topic associated included in the social assessment of dashboard

Stakeholder group	Social topics
Workers	Health and safety; Wages; Social benefits; Working hours; Child labour; Forced labour; Discrimination ; Freedom of association and collective bargaining ; Employment relationship; Training and education; Work-life balance; Job satisfaction and engagement
Local communities	Health and safety; Access to tangible resources ; Local capacity building ; Community engagement; Employment

Having selected the stakeholder group to be investigated, the data inventory compels the following steps: firstly data collection (at site level) for each life cycle stage (LCS_i indicator), and secondly, data allocation to the functional unit by means of an allocation factor (LCS_i allocated indicator).

ALLOCATION

The allocation (retrieved from the Handbook) has been modified to suit MM case studies, based on data availability and the contextualization of manufacturing plant management.

As a consequence, the following new formula of allocation is used(9):

Formula (9):

$$Allocationfactor = \frac{P_{site} \times H_{empl.site} \times 52weeks}{p_{productionline} \times h_{empl.productionline} \times 52week}$$

in which

- P site stands for the “number of employees at the site”;
- p production line means the “number of employees working at the specific production line”;
- H site: “total production at site level”;

- h production line: “total production of the product assessed”.

In order to be consistent, the same units of measurement should be used in reference to “H” and “h” data [i.e. kg; ton; unit; etc.].

AGGREGATION

Ultimately in the *aggregation* step, the allocated value for each life cycle stage is aggregated using the PLC indicator. The handbook provides two formula for the aggregation of the allocated values of the LCSi indicator product to the PLC values (product life cycle) according to the nature of indicator (absolute number or percentage).

More precisely, the PLC indicator values are elaborated according to a referencing step in which they are compared to reference values in order to evaluate the relative positive or negative performance of the product in the social impact assessment. The performance value (PV) is calculated for each indicator comparing the PLC indicator with the reference value (RV) of the indicator, according to the following principles:

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

An attempt was made to identify reference values specifically targeting the automotive sector (i.e. statistic values, best performances of the sector, normative limits). These were impossible to identify because they could not be measured using the same indicators and because of the difficulties, at the present time, in obtaining the relative statistics or directives. The social topic score is a dimensionless number that represents the impact of the product with regard to a social topic and is calculated by aggregating performance indicators.

6. IMPROVEMENT STRATEGIES TO REDUCE PRODUCT ENVIRONMENTAL IMPACT

> *"History teaches us that men and nations*
> *behave wisely once they have exhausted all other*
> *alternatives". (Abba Eban)*

In the preceding chapters 1, 2 and 3, the main motivators that pushed MM to react promptly to global issues were set out, as well as the area of intervention. The company's sustainability plan at the macro-level was explained in chapter…. Instead, the following chapters focus attention on the micro-level, thus,at product level. The methodologies and tools used to accomplish product impact were discussed in chapter 3; in addition, the methodologies which have been adapted to the MM context were presented in chapter 5. The present chapter 6 provides a general overview of the main improvement drivers for reducing the product impact, considering as a primary issue environmental impact reduction. The strategies which take their inspiration from the primary actions of car-makers were discussed in chapter 2. In short, improvement strategies can be grouped according to three criteria. The analyses are performed through a comparative assessment between a reference (standard design) and one or more alternatives (innovative design/s) for the given component. The main areas of intervention involve the following systems: i) drivetrain, ii) interior, iii) suspension and chassis, iv) powertrain, v) electronic and lighting and vi) exhaust. The selection of the product to be analysed is primarily based on the volume of sales, thus enabling a large scale development so as to be more effective. Other criteria are specific to the strategy and will be discussed in the following paragraphs.

6.1 FIRST STRATEGY: LIGHTWEIGHTING

Basically, the lightweighting strategy aims at reducing fuel consumption and exhaust pipe emissions, which chiefly occur during vehicle use. In this first strategy, component weight reduction is obtained through the substitution of material/s. Generally, the choice of the material assumes strategic importance since it directly affects the environmental performance of a product in terms of the properties of the materials, their manufacturing and weight, but it may also be the cause of technological and economic constraints. Therefore, a balance between the diminution of environmental impact and component function is necessary. The heaviest materials used for automotive applications are undoubtedly iron and steel. The main intention is to replace the heavy-materials with lower density ones. For this purpose, the R&D team concentrates its attention on the use of lighter materials such as aluminium and composites, which do not compromise component functionality. The primary criteria used in the selection of alternative materials are their technical properties; subsequently, a cross examination of several lighter material options are put on the table and confronted by means of LCA analysis. In the selection of alternative material, it is important to bear in mind the location of the component. Naturally, a different performance is required depending on whether the materials are intended to be used for a vehicle's interior system or powertrain; like the interior parts, the powertrain drive system requires high levels of component shock absorbing, in terms of mechanical and thermal stress. This is due to the fact that the components located under the bonnet are exposed to sharp thermic delta and humidity conditions, therefore criteria, such as the coefficient of thermal expansion, play a key role in this problem However, the present dissertation does not focus attention on the selection of the attributes of functional requirements as this step has previously been verified as necessary condition for the environmental impact analyses. As to the strategies regarding the substitution of materials, further case study applications were carried out in this field. First of all, because new high-resistance materials are currently available for application in the automotive sector; and secondly, the change in materials implicates less investment. Overall, the substitution of materials was carried out by: i) a complete substitution of heavy metals with plastic-base materials, ii) a partial substitution of heavy metals with plastic-based materials, iii) replacement with lighter plastic compounds and iv) lighter reinforcement for plastic compounds. Over recent years, plastic materials have increasingly been gaining ground due to their greater effectiveness, resulting in a decrease in the weight of components, while providing performance results comparable to metals. In fact, there have been great strides in the development of plastic material. An overview of the application of case studies in lightweighting application is reported in Table 10.A nearly example of the substitution of metals with plastic material involves a bulky component: a front suspension crossmember (CM). In particular, two lighter materials were tested as a substitution for steel: an aluminium alloy (CM1) and a high-resistance vinyl ester resin reinforced with CF (CM2). It is significant to notice that this change of materials led to a reformulation of component production technology and the down streaming life cycle management. This case study offers an example of how the life cycle phases of a component are correlated, and how the environmental benefits intended to be achieved at a specific stage, such as lightweighting to reduce use impact, can sometimes positively affect other dimensions consequently. For the CM case study it translates into: i) a simplification of the manufacturing technology, ii) a reduction in the time cycle, iii) the reduction in the expenditure of energy and auxiliary materials iv) the upgrading of the recovery of materials at EoL.

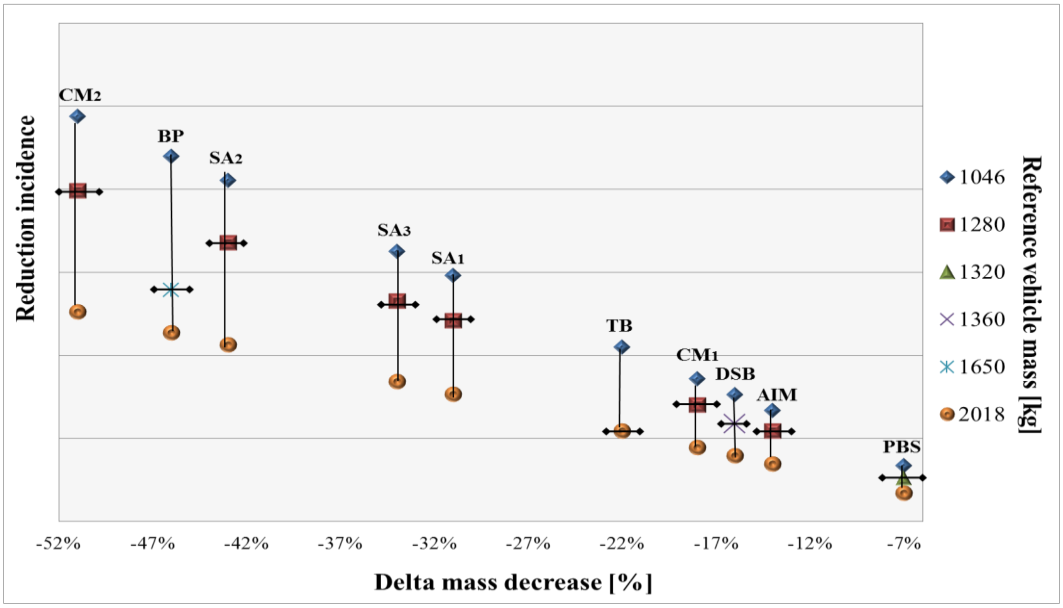
Another strategy is to partially substitute metals with a plastic compound: these applications regard different parts of the vehicle (interior, drivetrain and suspension systems). For interior and suspension parts the most stringent restrictions involve the response to stress behaviour. For this purpose, reinforcement fibres are inserted within a plastic matrix, in order to make the materials more stable during periodic or impulsive stress. At present, the most common mechanical strength used in automotive application are glass fibres and carbon fibres. The performance that can be achieved, in fact, permit the replacement of High Resistance Strength Steel with a one-single unit structure of metal insert, co-moulded with plastic material. This is the case of the Magneti Marelli base control arm, where the steel is substituted with two possible inserts (aluminium or steel) co-moulded by a polyamide-based material reinforced with glass fibres. Another significant achievement in this regard is the total substitution of co-moulded metals with a single plastic-reinforced material. One case involves the brake pedal component where the thermoplastic co-moulded metal insert is replaced by an innovative material produced from a polyamide matrix doubly reinforced with glass and carbon fibres mixed together. However, the challenge is to attempt an increase in the use of plastic for other vehicle locations (parts), such as that of the powertrain. The critical aspect related to the employment of plastic for powertrain application is that the requirements for materials regarding mechanical, thermal and electrical performance are demanding since powertrain components operate under severe work conditions [high vibrational stress, humidity, high temperature...]. The performance of plastics is still critical in overcoming this workload condition. Nevertheless, efforts are continuously being made in order to find high-resistance composites, as demonstrated by use of a thermoplastic material which was found to be suitable for a component that operates within the powertrain system: a throttle body. To be more specific a PET-GF, in replacement of an aluminium housing part, proved to conform to TB functional and performance requirements. Moreover, the substitution of this material for the manufacturing of the housing involved a formulation of the TB design with the elimination of other sub-components, thus further reducing the component’s weight. Other intended applications are for the substitution of a component, already produced with plastic materials, with a lighter one. This is the case of the AIM, where a lower-density plastic matrix (PP) substitutes the previous PA6, with the advantage of a shortening of the manufacturing time cycle, but without any design or technological changes being necessary. Similar advantages have been achieved in the dashboard panel case study, where the standard PP-reinforcement has been replaced with an innovative (HGM). Another example of reinforcement substitution was applied to the pedalbox support part, with the use of a bio-composite material; the ultimate aim is to avoid toxic substances that occur with the production of synthetic fibrer such as glass fibres and carbon fibres. Further examination regards the typology of plastic performance and in particular the comparison between thermoplastic and thermoset behaviour for an automotive lighting reflector. For this purpose, the reference thermoset-material (PEI) was compared to an equal thermoplastic performance material (PES).

Table 10 – Case studies overview of lightweighting strategy, with reference on component system, mass decrease and chose in action.

System	Component	Standard Design	Innovative Design	Weight Decrease	Strategy
Drivetrain	Air Intake Manifold [AIM]	PA6 GF30 *(1.87 kg)*	PP GF35 *(1.60 kg)*	-14%	Replace with an alternative thermoplastic
	Throttle Body [TB]	Alalloy (partially) *(0.86 kg)*	PET GF50 (partially) *(0.67 kg)*	-22%	Replace with thermoplastic composite
Interior	Dashboard [DSB]	PP Talcum25 *(4.73 kg)*	PP HGM23 *(3.95 kg)*	-16%	Replace reinforcement filler
	Pedal box support [PBS]	PP GF30 *(0.87 kg)*	PP NF45 *(0.81 kg)*	-7%	Replace reinforcement filler
	Brake pedal [BP]	Steel + PA66 GF60 *(1.02 kg)*	PA66 CF15 GF10 *(0.55 kg)*	-46%	Replace with one single unitary structure of thermoplastic composite
Suspensions and chassis	Crossmember [CM$_1$]	Steel *(19.00 kg)*	Al alloy *(15.65 kg)*	-18%	Replace with aluminum
	Crossmember [CM$_2$]	Steel *(19.00 kg)*	Vinyl ester CF53 *(9.36 kg)*	-51%	Replace with thermoplastic composite
	Suspension arm [SA$_1$]	Steel *(2.23 kg)*	Secondary Al + PA66 GF60 *(1.28 kg)*	-43%	Replace with aluminium and thermoplastic composite
	Suspension arm [SA$_2$]	Steel *(2.23 kg)*	Steel + PA66 GF60 *(1.53 kg)*	-31%	Partially substitution with thermoplastic composite
	Suspension arm [SA$_3$]	Steel *(2.23 kg)*	Steel + PA66 40CF (1.295 kg)	-42%	Partially substitution with thermoplastic composite
Electric and electronic	Reflector	PEI *(0.38 kg)*	PES *(0.25 kg)*	-34%	Replace with thermplastic material

As with the increase in the lightweight effect, the selection of the component is based on its mass. The higher the percentage decrease, the more effective the strategy is. Another important factor to consider is the component's mass portion of incidence within the entire vehicle selected if it was found that greater marginal contributions are attributed for the high percentage of mass decrease in lighter vehicles. These observations are reported in Figure 38, where a sensitivity impact analysis has been performed considering mass decrease parameters in relation to various vehicle targets. In order to observe a possible incidence slippage, different scenarios are presented for each component, changing motor vehicle calibrations and mass. For each component the reference vehicle is marked with a black line (i.e. considering BP the reference is 1650). The greatest marginal contribution observed is on the second strategy application of crossmember (CM2), followed by SA2 and BP; whereas the lesser are attributed to AIM project and PBS.

Figure 38 – Sensitivity analysis of the components mass decrease incidence reduction on reference vehicle.



More insight on these case study applications are available and presented in literature, considering a comprehensive examination at a general level (Maltese et al., 2016; Delogu et al., 2018). Other papers are specifically focused on the main insight stemming from the application of impact assessment methodologies on a specific component: i) AIM (Delogu et al., 2015); DSB (Delogu et al., 2016),CM1 (Maltese et al., 2017), TB(Delogu et al., 2018), PBS(Maltese et al., 2018), PB (Maltese et al., 2018).

6.2 SECOND STRATEGY: LAYOUT OPTIMIZATION

Parts of the case studies regard the layout optimization strategy to optimize component layout. This second strategy is determined though the production technology variation. The innovative technologies proposed are part of sustainable programmes aimed at implementing sustainable manufacturing principles. Two drivetrain components are based on this strategy application: the muffler and the fuel tank (Table 11). In particular, in the standardized manufacturing process, the technology used to realize the muffler envelope is the rolled technology. On the contrary, the innovative muffler layout is created with a stamped envelope. The change of technology allows for a decrease in the input of materials due to the final layout structure obtained. In the standard technology the envelope is rolled around the glass fibre while in the innovative technology the two shells produced are welded. In the case of the fuel tank, the technologies under examination are: the blowmoulding manufacturing process (reference) and the injection moulding (light), aiming at a layout optimization to reduce the leakage points. The advantage that the new tested technology brings is due to the reduction of high-environmental impact material (EVOH layers). Injection moulding means the integration of components/functions and high thickness control (fuel permeation and weight reduction). The welding of two shells after injection moulding allows a lay-out optimization in order to reduce the potential leakage points. The production process of the 2 shells is based on over-moulding injection technology, carried out on a unique injection machine equipped with 2 injection units and a rotary table, usable for the production of "2 components" (2K) parts. The injection cycle begins with a first step of moulding the inner layer of the component on the first side on the machine. After rotation of the mould, the second component is over-moulded onto the first one, on the other side of the machine. This process allows a cycle time reduction, a lean process (2 shots on the same machine), a better balance of the injection pressure and a good adhesion between the 2 layers. The above process is considered innovative when compared with a traditional blow moulding process based on extrusion, a specific transformation starting from a vertical extrusion of a parison (a multi-layered tube of melted polymers).

Table 11 - Case studies overview of layout optimization strategy, with reference to component system, mass decrease and choice in action.

System	Component	Standard Design	Innovative Design	Weight Decrease	Choice in action
Drivetrain	Muffler	Rolling (3.61 kg)	Stamping (3.53 kg)	-2%	Envelope layout optimization through technology variation
	Fuel tank	Blowmolding (7.00 kg)	Laser welding (4.72 kg)	-33%	Layout optimization with leakage points reduction

6.3 THIRD STRATEGY: COMPONENT EFFICIENCY

The thirst strategy application regards the auxiliary module lighting source substitution. The auxiliary takes part within the vehicle lighting system and is required to guarantee the functionality listed in Table

12. The lighting system of a motor vehicle consists of lighting and signalling devices mounted or integrated to the front, rear and sides. The component efficiency has been evaluated for an operative time during component use over a specific life mileage (expressed in km) and in hours of operation.

Table 12 - Headlight module lighting and signalling function.

1) Lighting functions (to illuminate the road):
•Low Beam (Passing beam) (Dipped-beam); *•High Beam (Driving beam) (Main-beam).*
2) Light-signalling functions (to be seen):
•Direction-indicator lamp; *•DRL (Daytime Running Lamp);* *•Front position lamp;* *•Side marker lamp;* *•Side reflex;*

In particular the present project regards the substitution of a standard *halogen auxiliary module* lighting-functioning[low version] with a full *LED auxiliary module* lighting functioning [high version]. The main description of the case study application is reported in

Table **13**. The main improvement driver is the decrease of the energy absorbed during component operation. Table 14lists the maximum consumption par the different halogen and LED technology. The LED variation leads to a change of the light source technology operation but also to the entire geometry design of the headlight module and the sub-component reformulation.

Table 13 - Case study overview of component efficiency strategy.

Component	Standard Design	Innovative Design	Lighting function	Strategy
Auxiliary module	Auxiliary module with *halogen turn indicator*, LED Daytime running /position light. (3.562 kg)	Auxiliary module *with LED turn indicator*, LED Daytime running /position light. (5.589 kg)	1. Standard use Halogen and one LED and 2. Innovative Several high power LED's	Reduction of energy absorption during component operation

Table 14 – Energy absorption value (expressed in watt) for halogen and LED technology considering maximum [V] and minimum values [A].

		V	A	W	
Standard auxiliary module	Turning Indicator	13.5	1.56	21	23.31
	Daytime Running Lamp (DRL)	6.6	0.35	2.31	
Innovative auxiliary module	Turning Indicator	6	0.35	2.1	12.6
	Daytime Running Lamp (DRL)	15	0.7	10.5	

7. FIRST STRATEGY: LIGHTWEIGHING

In chapter 7 are discussed with major details each steps of the analysis for each component regarding lightweighting application strategy. The structure is presented according to the ISO 14040 for LCA and eLCC respectively. To start, a brief description of the “goal and scope” of the study is presented, providing an explanation of component functionality and location within vehicle system. The following studies regard the assessment of a current component design (named standard) with a novel proposal (named innovative). Therefore, the main results regard the methodology applicability in terms of data availability, indicators relevance and appropriateness, and results presentation and interpretation are presented. Outcomes in terms of component sustainability could be retrieved only concerning environmental and economic assessment; however, more insights could be obtained in a comparative analysis.

7.1 AIR-INTAKE MANIFOLD

This project focuses on the environmental impact assessment analysis between *two different materials* for the production of a specific automotive component: an Air Intake Manifold (hereafter AIM). The method adopted is a combination of a ***Life Cycle Assessment (LCA)*** and a ***Life Cycle Costing (LCC)*** as a part of Life Cycle Sustainability Assessment (LCSA) analysis. The purpose is to make evidence on which of the two materials application cause mostly the environmental impact and economic expenditure, considering the full product life cycle. For this purpose, the perimeter of the analysis include all the phases upstream and downstream of the MM production stage, performing in this way what is so called “cradle to grave” approach analysis. Overall, the main goals of the project are:

- verify applicability of LCA and LCC as a supporting tools to “identify the main sustainability hotspots in the product life cycle - especially regarding its technology function during its operation on the vehicle - therefore guide strategy development” and provide elements for production decisions for AIM production;
- develop data collection on environmental and economic impact of the materials profile regarding the manufacturing of the AIM and possible application for others components;
- create a model for the environmental assessment of a the specific materials;
- provide guidance on different product design proposals based on environmental and economic impact point of view.

7.1.1 GOAL AND SCOPE

The overall scope of the study is to quantify the environmental and economic impacts of the entire AIM life cycle, comparing two different materials to make the component shell. The standard materials is a *polyammide reinforced with a 30% of glass fibers [PA6-30GF]*, whereas the innovative material is a *polypropylene reinforced with a 35%in weight of glass fibers [PP-35GF]*. The main driver taken into account for improvement is the component *lightweighting* due to the lowering of innovative materials density, with respect of geometry design and production technology cycle.

The present analysis can be used to supply sustainability information to improve product performances in terms of:

- life cycle perspective to assess a balance among environment and economic point of view, two different materials for the production of a specific component to apply at macro-level;
- find insight in the specific context of manufacturing plant with focus on different materials performances for specific application in drivetrain application;
- quantifying energy and resource intensive processes and minimizing their impact.

In order to assess the environmental and economic impact of the standard and innovative AIM, a comparative LCA and eLCC between the two different design solutions has been accomplished. The main technical difference data of the two design solutions are reported in Table 15. The consequences of the materials variation is the shortening of time cycle, related to the molding phase.

Table 15 - Technical data of Air Intake Manifold design solutions.

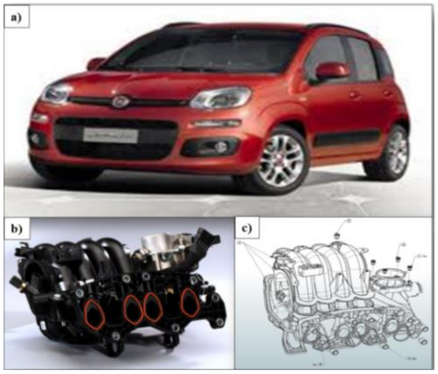
Features	Standard Design	Innovative design	Variation
Weight	1.18 [kg]	0.98 [kg]	Weight decrease (12%)
Parts	a) Central body (PA6GF30)	a) Central body (PPGF35)	Material
	b) Upper cover (PA6GF30)	b) Upper cover (PPGF35)	Material
	c) Lower cover (PA6GF30)	c) Lower cover (PPGF35)	Material
	d) Throttle body insert [Brass (P-CuZn40Pb2)]	d) Throttle body insert [Brass (P-CuZn40Pb2)]	-
	e) Insert [Brass (CuZn38Pb 1.5)]	e) Insert [Brass (CuZn38Pb 1.5)]	-
	f) Runner gasket [Fluorocarbon, Fluoroelastomer Rubber (FKM)]	f) Runner gasket [Fluorocarbon, Fluoroelastomer Rubber (FKM)]	-
	g) Throttle body gasket [Fluorocarbon, Fluoroelastomer Rubber (FKM)]	g) Throttle body gasket [Fluorocarbon, Fluoroelastomer Rubber (FKM)]	-
	h) Compression limiter [Steel (CF9SMnPb36, Riv.Fe//Zn8//C)]	h) Compression limiter [Steel (CF9SMnPb36, Riv.Fe//Zn8//C)]	-

Production Technology	Molding → Welding → Assembly sub-components	Molding → Welding → Assembly sub-components	Molding time cycle

7.1.2 COMPONENT DESCRIPTION

The air intake manifold (Figure 39) takes part in the vehicle drivetrain system. It ensures the optimal filling of the engine cylinders with a suitable mass of combustive agent, and carries out the function of integrating other engine supply control functions: fuel supply, fuel anti-evaporation system control, and engine operation point control. Hence it can also carry out the function of engine supply mechatronic module. The AIM basically consists of a volume of thermoplastic material with high thermal and mechanical resistance, composed by three parts made in injection moulding technology and joined by vibration welding: central body, lower cover and upper cover. The others components that complete the AIM product are: i) throttle body gasket, ii) runner gasket, iii) throttle body, iv) filter insert and v) compression limiters. The production technology of the shells (central body, upper and lower cover) involves an injection moulding machine: the polymer granules are fed through a hopper into the plasticizing cylinder of a press, are heated, softened and then injected into a mold cavity through which the component takes the shape. Through the thermoregulation system the workpiece is cooled, solidifies and is extracted from the cavity, at this point the machine is ready to begin a new production cycle.

Figure 39 – a) reference vehicle, b) standard Air Intake Manifold, c) exploded view.



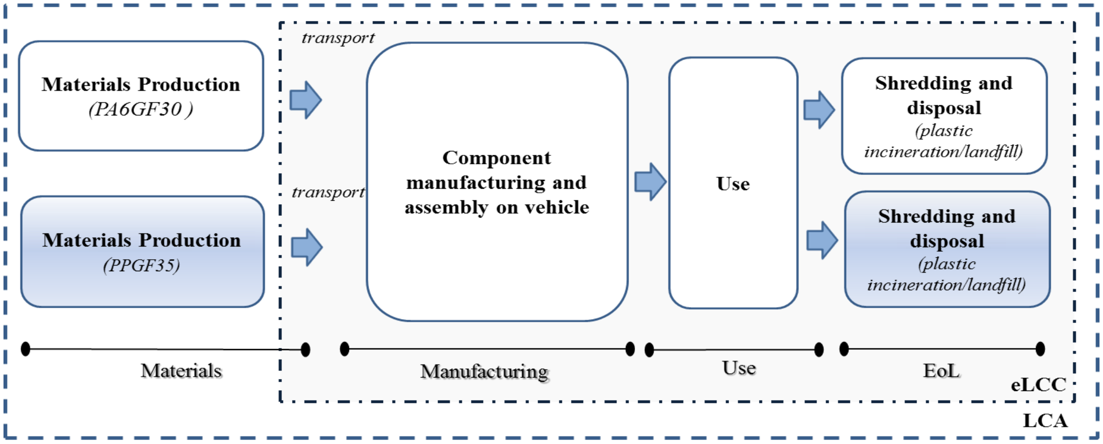
7.1.3 SYSTEM BOUNDARIES AND FUNCTIONAL UNIT

In this paragraph the product system and the system boundaries are described. Regarding the system boundary, LCA and LCC are conducted by defining product systems as models that describe the key elements of physical systems. The system boundary defines the unit processes to be included in the system. Ideally, the product system is modelled in such a manner that inputs and outputs at its boundary are elementary flows. The choice of the elements of the physical system to be modelled depends on the goal and scope definition of the study. The two AIM options are analyzed as integrated within the drivetrain system through all its life cycle, according to a “cradle to gate” approach, splitting it in the following macro-phases: materials, manufacturing, use, end of life and transport of each phase in between. For the present case study are considered the life cycle phase grouped according to:

- materials which includes raw materials extraction and their processing;
- manufacturing accounts for all the process involved within MM perimeter to produce the AIM;
- transport assess the impact attributed to all the shipments for the life cycle phases in between;
- use is based on component operation within the reference vehicle selected for a specific life time mileage;
- end of life: consists of all the process involved to recover/disposal of the materials (after vehicle dismiss) according to their typology.

Following Figure 40characterizes AIM life cycle phases for both scenarios. The two design solution differs for the: material and transport. The Functional Unit (FU) of the present analysis is one *automotive Air Intake Manifold* CAB FIRE 317 integrated within the drivetrain system, supporting and housing all the instrumentation for vehicle use, to be mounted on gasoline 1600 cm^3, (74 kW) car for 150,000 km on 10 years.

Figure 40 – Air Intake Manifold case study system boundary.



7.1.4LCA ANALYSIS

Here is presented the LCA methodology application on AIM design solutions.

7.1.4.1 LIFE CYCLE INVENTORY (LCI)

In this sub-paragraph data collection to quantify relevant inputs and outputs of the phases which compose product life cycle is described. Where possible process parameters (materials and energy flows) were obtained by direct measurements on industrial processes and/or estimation; in the others cases assumptions from GaBi 6.115 processes database have been used. In Table 16 and Table 17 a description of modalities used to collect data is reported. The materials compositions and production are grouped with the reference of Gabi datasets and data quality. The Use stage covers the operation of the muffler integrated within the exhaust system of the vehicle selected. It reflects the fuel consumption linked to the mass during the life time of a vehicle. To calculate impact imputable to the component operation over the vehicle life time [150,000 km], it was used an analytical model proposed by (Koffler and Rohde-Brandeburger 2010) considering the parameters in Table 18. The EoL management options have been modeled according to the AIM materials composition to separate plastics: from metal recovery process → fluff treatment in press machine [to obtain compacted fluff]. Energy consumption calculation is based on the mass of the sub-component to be treated according to the EoL options to recover/dispose certain material typology. The End of Life modelling includes the environmental burdens of recycling processes and grants credits for the recycled/ recovered materials.

Table 16 - LCA data collection standard design solution [PAGF30].

	Standard Design		
Life cycle phase	**Specification**	**Quantity** *(per FU)*	**Process** *(GaBi; ecoinvent)*
Materials	a)Polyamide 66 reinforced with 30% of Glass fibers (PA6GF30) - central body production	7.1x10-1 PA66; 3x10-1 GF	Polyamide 6 Granulate (PA 6) [Plastics] and Glass fibers (GF)
	b)Polyamide 66 reinforced with 30% of Glass fibers (PA6GF30) - upper cover production	3.16 x10-1 kg; 2.22x10-2 PA66; 9.48x10-3 GF	Polyamide 6 Granulate (PA 6) and Glass fibers (GF)
	c)Polyamide 66 reinforced with 30% of Glass fibers (PA6GF30) - lower cover production	4.4 x10-1 kg; 3.03x10-2 PA66; 1.32x10-2 GF	Polyamide 6 Granulate (PA 6) and Glass fibers (GF)
	d) Throttle body insert [Brass (P-CuZn40Pb2)] x4	9.6x10-2 kg	CuZn39Pb3
	e) Insert [Brass (CuZn38Pb 1.5)]	6.1x10-2 kg	CuZn39Pb3
	f) Runner gasket [Fluorocarbon, Fluoroelastomer Rubber (FKM)] x4	8.8x10-2 kg	NBR rubber

	g) Throttle body gasket [Fluorocarbon, Fluoroelastomer Rubber (FKM)]	4.6x10-2 kg	NBR rubber
	h) Compression limiter [Steel (CF9SMnPb36, Riv.Fe//Zn8//C)]	6.06x10-2 kg	Steel cast part alloyed
Manufacturing	1. Molding (upper and lower cover/lower and central body)	1.61 kWh	Electricity grid mix (IT)
	2. Welding (upper/central body and lower cover)	1.42x10-1 kWh	Electricity grid mix (IT)
	3. Assembly (sub-components)	1.4x10-1 kWh	Electricity grid mix (IT)
Logistic	Total segments distance travelled [2 sub-components suppliers and one material supplier [(PA6GF30)]	2430 km	Truck-trailer, Euro 5, 28 - 34t gross weight / 22t payload capacity
EoL	Shredding (within drained vehicle) → Materials separation → Metals recovery	1.4x10-2 kWh	Car shredder; Steel mill scales - scrap credit (open loop); Steel rebar (23%); Electricity mix (IT)
	Shredding (within drained vehicle) → Materials separation → Plastic incineration/disposal	5.55x10-2 kWh	Car shredder (Gabi); Electricity grid mix (IT); Plastic waste on landfill/Plastic incineration

Table 17 - LCA data collection standard design solution [PPGF35].

	Innovative Design		
Life cycle phase	**Specification**	**Quantity** *(per FU)*	**Process** *(GaBi; ecoinvent)*
Materials	a)Polypropylene reinforced with 30% of Glass fibers (PA6GF30) - central body production	8.91x10-1 kg 5.79x10-1 PP; 3.12x10-1 GF	Polypropylene Granulate (PP) and Glass fibers (GF)
	b)Polypropylene reinforced with 30% of Glass fibers (PA6GF30) - upper cover production	2.75 x10-1 kg 1.79x10-2 PP; 9.62x10-3 GF	Polypropylene Granulate (PP) and Glass fibers (GF)
	c)Polypropylene reinforced with 30% of Glass fibers (PA6GF30) - lower cover production	3.83 x10-2 kg 2.49x10-2 PP; 1.34x10-2 GF	Polypropylene Granulate (PP) and Glass fibers (GF)
	d) Throttle body insert [Brass (P-CuZn40Pb2)] x4	9.6x10-2 kg	CuZn39Pb3
	e) Insert [Brass (CuZn38Pb 1.5)]	6.1x10-2 kg	CuZn39Pb3
	f) Runner gasket [Fluorocarbon, Fluoroelastomer Rubber (FKM)] x4	8.8x10-2 kg	NBR rubber

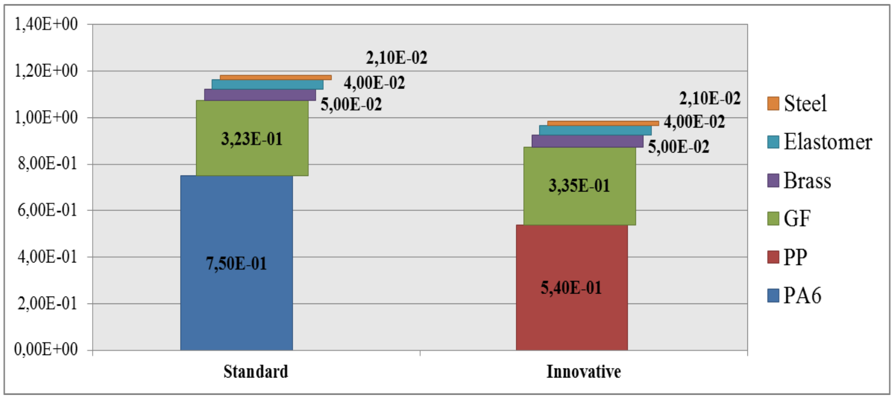
	g) Throttle body gasket [Fluorocarbon, Fluoroelastomer Rubber (FKM)]	4.6x10-2 kg	NBR rubber
	h) Compression limiter [Steel (CF9SMnPb36, Riv.Fe//Zn8//C)]	6.06x10-2 kg	Steel cast part alloyed
Manufacturing	1. Molding (upper and lower cover/lower and central body)	1.17 kWh	Electricity grid mix (IT)
	2. Welding (upper/central body and lower cover)	1.42x10-1 kWh	Electricity grid mix (IT)
	3. Assembly (sub-components)	1.4x10-1 kWh	Electricity grid mix (IT)
Logistic	Total segments distance travelled [2 sub-components suppliers and one material supplier [(PA6GF30)]	2430 km	Truck-trailer, Euro 5, 28 - 34t gross weight / 22t payload capacity
EoL	Shredding (within drained vehicle) → Materials separation → Metals recovery	1.4x10-2 kWh	Car shredder (Gabi); Steel mill scales - scrap credit (open loop); Steel rebar (23%); Electricity grid mix (IT) (Gabi)
	Shredding (within drained vehicle) → Materials separation → Plastic incineration/disposal	4.6x10-2 kWh	Car shredder (Gabi); Electricity grid mix (IT); Plastic waste on landfill/Plastic incineration

Table 18 - LCA data collection “Use phase”, vehicle technical data and model parameter for Air Intake Manifold.

Technical data referring to car model equipped with the Air Intake Manifold		
Vehicle technical characteristic	Model	gasoline 1600 cm3, (74 kW)
	Emission stage (e.g. EURO5)	EURO5
	Mass [kg]	1280
	Motorway per-km CO_2 emission [g/km]	164
	Mixed consumption [l/100km]	6.4
Operation	Vehicle life time [km] - dm	150,000
Analytic model [NEDC]	Mass induced fuel consumption [l/100km*100kg] - FRV_PMR [Gasoline] - fm	0.15
Mass [m]	Vehicle equipped with standard air intake manifold [kg]	1.18
	Vehicle equipped with first innovative air intake manifold [kg]	0.98
Fuel density	Gasoline [kg/dm^3]	0.74
Specific consumption [kg/kg fuel]	CO_2 emissions generated during the consumption of 1 kg of fuel [kg CO_2/Kg fuel] – f_{CO2}	3.12
	SO_2 emissions generated during the consumption of 1 kg of fuel [kg SO_2/Kg fuel] - f_{SO2}	0.00015

In the modeling of the AIM life cycle, the packaging consumption has been excluded since materials are always recovered for the same purposes. Furthermore, the production of the compression limiters, of the gasket and of the brass insert has been excluded for unavailable information. Below (Figure 41) is reported the materials breakdown according to their composition and weight contribution on standard and innovative design. The two components design differs from the plastic matrix which for the standard is constituted by PA6, whereas for the innovative is PP. Other difference in terms of materials composition is the quantity of GF, which is slightly increased, in the innovative design.

Figure 41 – Materials composition breakdown air intake manifold design solutions.



7.1.4.2 LCA LIFE CYCLE IMPACT ASSESSMENT (LCIA)

In this section life-cycle environmental impact has been calculated on the basis of data gathered during the inventory; it has been done by applying *Classification* and *Characterisation* to LCI data according to ISO 14040 standard guidelines. The results of Life Cycle Impact Assessment are reported below; this has been obtained according to *CML 2001 Apr. 2016*regulations, the *Primary Energy Demand (PED)* category from renewable and non-renewable resources (gross cal. value) has been considered. Results are presented in Figure 42in a form to show, for each class of environmental impact, the contribution of each life cycle stage, on the total impact, for the two design solutions, whereas the total impact percentages delta [Δ%] for each impact indicator are reported in Table 19.

Figure 42 – LCIA results air intake manifold.

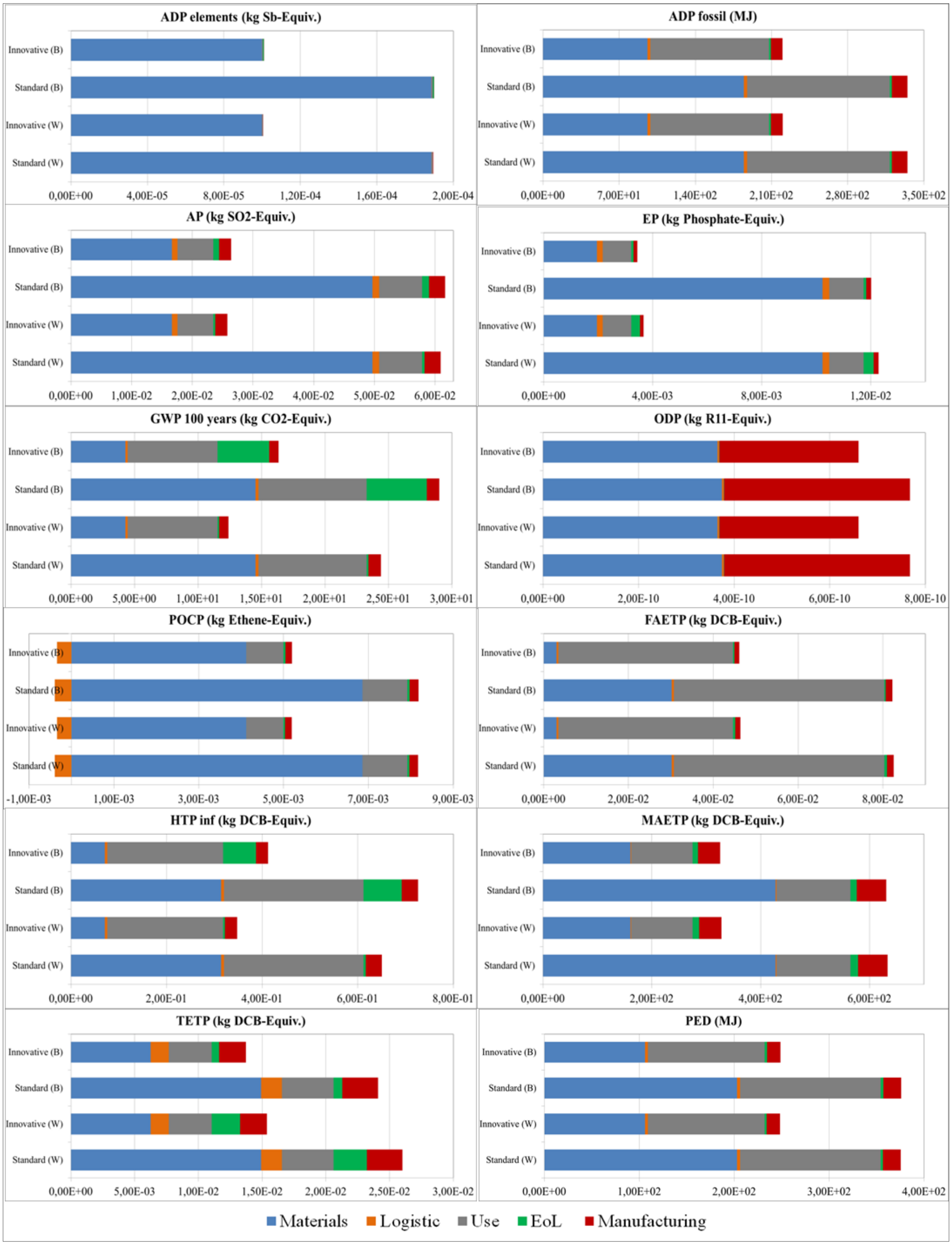


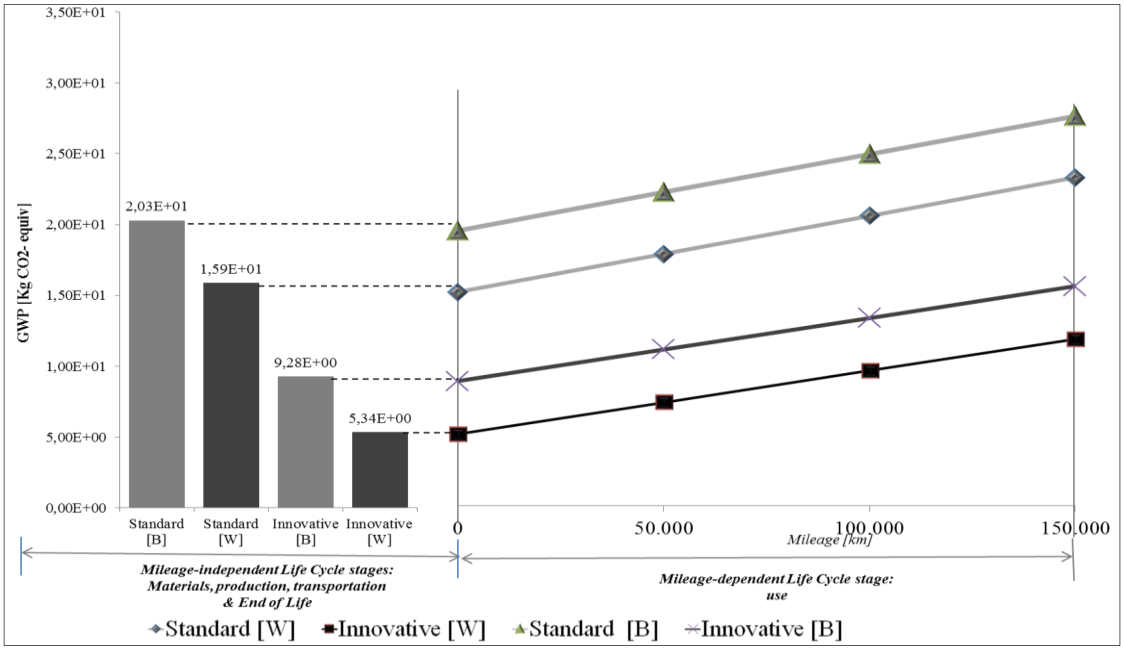
Table 19 - Air intake manifold total impact percentage delta decrease (-) increase ( ), worst option (W) and best option (B).

Impact categories	Δ% (W)	Δ% (B)
CML2001 - Jan. 2016, Abiotic Depletion (ADP elements) [kg Sb eq.]	-88%	-88%
CML2001 - Jan. 2016, Abiotic Depletion (ADP fossil) [MJ]	-52%	-52%
CML2001 - Jan. 2016, Acidification Potential (AP) [kg SO2 eq.]	-136%	-133%
CML2001 - Jan. 2016, Eutrophication Potential (EP) [kg Phosphate eq.]	-235%	-250%
CML2001 - Jan. 2016, Freshwater Aquatic Ecotoxicity Pot. (FAETP) [kg DCB eq.]	-78%	-78%
CML2001 - Jan. 2016, Global Warming Potential (GWP 100) [kg CO2 eq.]	-97%	-77%
CML2001 - Jan. 2016, Human Toxicity Potential (HTP inf.) [kg DCB eq.]	-87%	-76%
CML2001 - Jan. 2016, Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	-93%	-94%
CML2001 - Jan. 2016, Ozone Layer Depletion Potential (ODP) [kg R11 eq.]	-16%	-16%
CML2001 - Jan. 2016, Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	-60%	-60%
CML2001 - Jan. 2016, Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	-69%	-75%
Primary energy demand from ren. and non-ren. resources (gross cal. value) [MJ]	-51%	-51%

GHG EMISSIONS BREAK-EVEN

In Figure 43is reported the GHG emissions of CO_2 over the life cycle contribution of the standard and innovative AIM. The total amount is separated according to static attribution, as a sum of the AIM LC occurred during the upstream and downstream activities (materials extraction and production, logistic, component manufacturing and EoL) with reference of the component operational use. Overall are presented four scenarios considering the EoL differentiation as worst option [W] considering plastic landfill and, on the contrary, the case where plastics are incinerated [B]. The separation among the LC contribution is due to the fact that, CO2 emissions are directly dependent on component use; in fact, the more the vehicle runs the more emissions are generated. The highest emissions are attributed to the heaviest component considering the plastic incineration options, whereas the lowest emissions occurs in the worst scenario case for the lightest component. No break-even point is observable since the standard solution accounts for the highest amount of CO2 emissions from the very beginning.

Figure 43 – GHG emissions break-even air intake manifold.



7.1.4.3 LCA INTERPRETATION

In this final section the results obtained (and Figure 43) and previously shown for each process separately are now compared and interpreted. From the LCIA results in Figure 42, could be seen that, among all the LC phases, the major contribution is given by materials and use categories, with the exception of parts of indicators. Each indicator is representative of a specific environmental issue and, in this context it is particularly influenced by a specific portion of product life cycle. For that reason indicator as *ADP elements* are particularly affected by abiotic materials depletion withdraw. Other impact categories particularly influenced by materials consumption are: ADP fossil, AP, EP, POC, MAETP. The reason behind is due to the fact that plastic worsen the effect for their high impact on production stage: high numbers of chemical, energy expenditure are the main consequence behindhand. Other categories are more sensible to the component operation as GWP, FAETP, ADPfossil and PED. The aforementioned indicators are affected by the release of the substance generated from tailpipe emissions and from fuel consumption. Other category as ODP feels the effect of the amount of electricity consumption which mostly occurs during AIM manufacturing. Overall the innovative solution brings an impact reduction, with more emphasis on ADPelements, EP, AP, GWP and HTP with a percentage more than 80% (Table 19). The favourable condition is brought by the employment of a less impacting plastic as PP in substitution of the PA6, especially considering materials and use point of view. No sensible differentiations are perceived from the adoption of the [W] and [B] scenario, except for the GWP. The Manufacturing, Logistic and EoL categories present a minor contribution to the total components of components life cycle impact. Despite the negligible effect, it is important to underline the slight advantages that the innovative design brings in terms of transport reduction, due to the reduction of transport distance and to the reduction of manufacturing impact due to the lowering of energy consumption with respect of manufacturing process condition. Looking atFigure 43, the gap among standard and innovative is increased in the best options, due to the increase of CO_2 emissions generation during incineration process.

7.1.5 ENVIRONMENTAL LIFE CYCLE COSTING

The following section describes the eLCC analysis of the AIM case study.

7.1.5.1 LIFE CYCLE INVENTORY [LCI]

The unit costs are given in Table 20 and according to what described in CHAPTER 5 (paragraph 5.1.2 *LCC methodology in Magneti Marelli*). Regarding the environmental eLCC the total cost is attributed from conventional LCC with the addition of the cost derived by the CO_2 emissions generated during component LC (accounting materials, manufacturing, logistic, EoL and use over 150,000 kilometres of use) and their damage cost [€/kg emissions]. Valuations of specific environmental damage cost are provided by the Clean Vehicles Directive 2009/33/EC [30]. CO_2 emissions were already calculated from LCA analysis.

Table 20 – LCC inventory air intake manifold standard and innovative design solutions.

Standard Design			
Life cycle phase	**Flow (*per FU)**	**Unit cost**	**Source**
Transports	Transports (fuel and driver) per km	1.1 €/km	*Primary data*
	Item quantity	1.18 kg/FU	
	Distance travelled	2,430 km	
	Truck gross weight	35 t	
	Truck payload	27 t	
Manufacturing	Electricity	0.12 €/kWh (average European)	*Eurostat, 2018*
Use	Gasoline	1.46 €/litre (avg European price)	*IEA, 2018*
	CO_2 emissions cost	4.00×10^{-5} €/gCO_2	*European Commission*
EoL	Electricity	0.12 €/kWh (average European)	*Eurostat, 2018*
	Plastic disposal [Worst case]	0.1 €/kg	*Primary data*
	Non-metal recovery	0.38 €/kg	
	Metals recovery	0.19 €/kg	

Innovative Design			
Life cycle phase	**Flow (*per FU)**	**Unit cost**	**Source**
Transports	Transports (fuel and driver) per km	1.1 €/km	*Primary data*
	Item quantity	0.98 kg/FU	
	Distance travelled	2,430 km	
	Truck gross weight	35 t	
	Truck payload	27 t	
Manufacturing	Electricity	0.12 €/kWh (average European)	*Eurostat, 2018*
Use	Gasoline	1.46 €/litre (avg European price)	*IEA, 2018*
	CO_2 emissions cost	4.00 x 10^{-5} €/gCO_2	*European Commission*
EoL	Electricity	0.12 €/kWh (average European)	*Eurostat, 2018*
	Plastic disposal [Worst case]	0.1 €/kg	*Primary data*
	Non metal recovery	0.38 €/kg	
	Metals recovery	0.19 €/kg	

7.1.5.2 LCC IMPACT ASSESSMENT [LCIA]

In Table 21are presented the total cost attributable to the AIM from MM perspective, internalizing the cost attributable to user during vehicle use and EoL management to recover and/or disposal the relative materials. Economic assessment results are described according to the following cost categories: manufacturing, transports, use and end-of-life. The perspective used in the analysis could mainly give information to the producer for the evaluation of the innovative convenience of the adoption of the innovative design. Only the costs of materials and sub-components acquisitions have been excluded. Despite the only difference regards the cost of acquisition of the PA6GF with PPGF.

The calculation of each contribution has been accomplished following the rules reported in CHAPTER 5 (paragraph 5.1.2 LCC methodology in Magneti Marelli) and considering the following assumptions:

- for transport considering the logistic management along AIM LF, therefore considering fuel expenditure and driver salary;
- for manufacturing the cost attributable to each production item considering the contribution of energy expenditure, which is the only variation among standard and innovative costs scenario;

- for use the total fuel consumption during vehicle life-time mileage of 150,000 km attributable to each component, multiplied by the average European cost of gasoline fuel, in addition the calculation takes into account the discount method which results are illustrated in Figure 44;
- for EoL the cost attributable to the disposal and/or recovery of each material flow within the dismantle line for materials recovery.

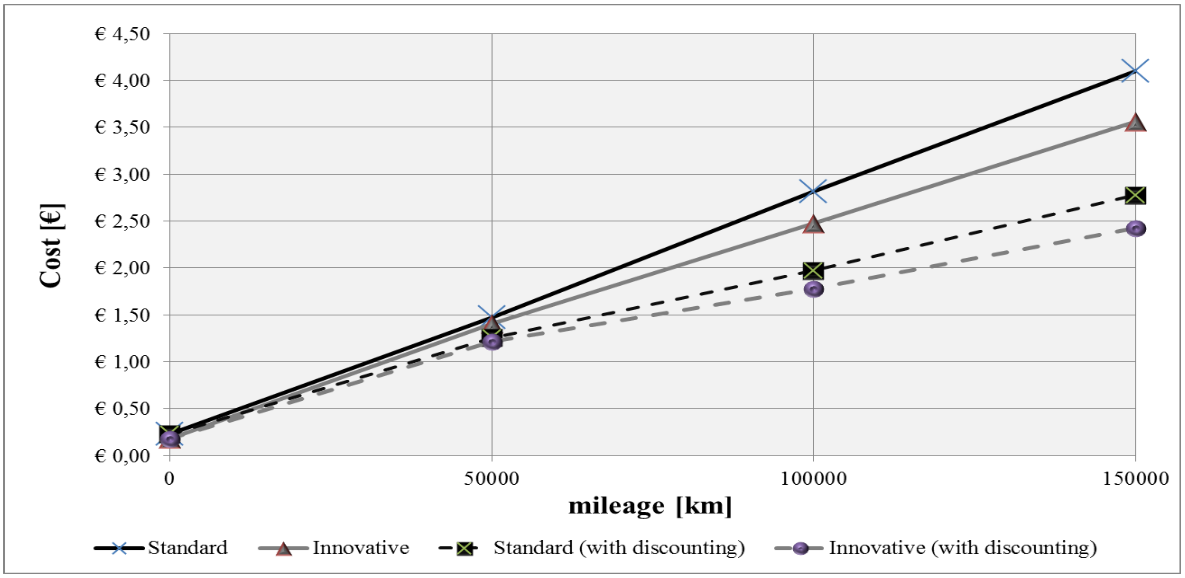
The eLCC results in a total cost of standard solution of 4, 28 € and of innovative 3, 56 €.

Table 21 - eLCC results air intake manifold.

Reference	Flow	Standard unit cost [W] [€/FU]	Innovative unit cost [W] [€/FU]	Standard unit cost [B][€/FU]	Innovative unit cost [B] [€/FU]
Transport [€/FU]	Distance travelled	*€ 0,09*	*€ 0,08*	*€ 0,09*	*€ 0,08*
Manufacturing [€/FU]	Production	*€ 0,23*	*€ 0,18*	*€ 0,23*	*€ 0,18*
Total cost (MM perspective)		***€ 0,32***	***€ 0,26***	***€ 0,32***	***€ 0,26***
Use [€/FU]	Fuel	*€ 3,87*	*€ 3,23*	*€ 3,87*	*€ 3,23*
	Externalities	*€ 0,001*	*€ 0,0005*	*€ 0,001*	*€ 0,001*
Total cost (user perspective)		***€ 3,87***	***€ 3,23***	***€ 3,8702***	***€ 3,2273***
EoL [€/FU]	Materials separation	*€ 0,01*	*€ 0,01*	*€ 0,01*	*€ 0,01*
	Materials recovery/dispose	*€ 0,08*	*€ 0,07*	*€ 0,08*	*€ 0,07*
Total life cycle cost[€/FU]		***€ 4,28***	***€ 3,56***	***€ 4,28***	***€ 3,56***

Figure 44 depicts the fuel consumption cost break-even analysis over the vehicle 150,000 km mileage of use. A sensitivity analysis reporting a comparison among discounting and non-discounting calculation has been accomplished. From the line chart could be observed a break-even point since the economic convenience of the innovative AIM production starts from production stage.

Figure 44 – Fuel cost break-even air intake manifold.



7.1.5.3 eLCC INTERPRETATION

From Table 21 could be distinguished the contribution of the total cost attributable to the AIM LC activities. Indeed the most spending takes places during vehicle use, due to the fuel consumption and cost. Different consideration could be retrieved considering the different actors perspective. From MM perspective, the implementation of the innovative solution means a production cost decrease of 17%, without considering the material cost. Further benefits are identified from user perspective, considering a cost decrease of fuel consumption, which increases proportioned to the mileage traveled. The less materials are processed in the EoL, the lower cost incomes are generated. To sum up, the implementation of the lighter innovative materials decrease the total cost over each LC dimensions, with more benefits related to the user perspective.

7.2 PEDALBOX SUPPORT

This project focuses on the environmental impact assessment analysis between *two different materials* for the production of a specific automotive component: a Pedal box support (hereafter PBS). The method adopted is the ***Life Cycle Assessment (LCA)*** as a part of Life Cycle Sustainability Assessment (LCSA) analysis.

The purpose is to make evidence on which of the two materials application cause the most environmental impact, considering the full product life cycle. For this purpose, the perimeter of the analysis include all the phases upstream and downstream of the MM production stage, performing in this way what is so called “cradle to grave” approach analysis.

Overall, the main goals of the project are:

- verify applicability of LCA as a supporting tool to “identify the main sustainability hotspots in the product life cycle - especially regarding its technology function during its operation on the vehicle - therefore guide strategy development” and provide elements for production decisions for PBS production;
- develop data collection on environmental impact of the materials profile regarding the manufacturing of the PBS and possible application for others components;
- create a model for the environmental assessment of a the specific materials;
- provide guidance on different product design proposals based on environmental and economic impact point of view.

The component life cycle modelling has been implemented within Gabi software [6.115 DB].

7.2.1 GOAL AND SCOPE

The overall scope of the study is to quantify the environmental impacts of the entire AIM life cycle, comparing two different materials to make the component structure. The standard materials is a *polypropylene reinforced with a 30% of glass fibers [PP-30GF]*, whereas the innovative material is a *polypropylene reinforced with a 45% in weight of a woodchip [PP-45WC]*. The main driver taken into account for improvement is the component *lightweighting* due to the lowering of innovative materials density, with respect of geometry design and production technology cycle, as well as reduction of toxic emissions, introduce renewable materials benefit and replace synthetic materials as reinforcement with naturals.

The present analysis can be used to supply sustainability information to improve product performances in terms of:

- life cycle perspective to assess a balance among environment point of view, two different materials for the production of a specific component to apply at macro-level;
- find insight in the specific context of manufacturing plant with focus on different materials performances for specific application in interior part application;
- provide insight among the use of different fillers for plastic reinforcement purposes;
- analyse possible adoption of natural strength for vehicle plastic part use;
- quantifying energy and resource intensive processes and minimizing their impact.

In order to assess the environmental and economic impact of the standard and innovative PBS, a comparative LCA between the two different design solutions has been accomplished. The main technical difference data of the two design solutions are reported in Table 22. The consequences of the materials variation is the shortening of time cycle, related to the molding phase.

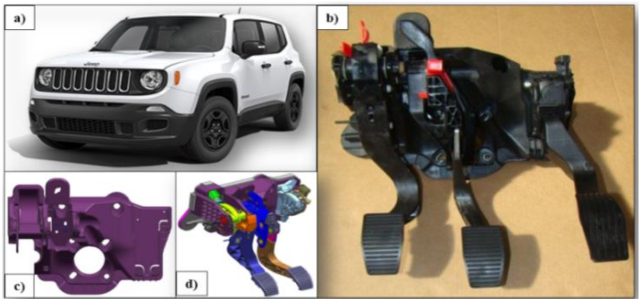
Table 22 – Technical data of pedal box support design solutions.

Features	Standard	Innovative	Variation
Weight (kg)	0.869	0.812	6.5% weight reduction
Part/s	compounding [Polypropylene reinforced with 30% glass fibers (*PP GF30)*]	compounding [Polypropylene reinforced with 45% woodchip (*PP NF45)*]	Reinforced filler change
Production technology	Injection Molding	Injection Molding	Invariant with shortening of *molding* time cycle (9%)

7.2.2 COMPONENT DESCRIPTION

The Pedal Box support takes part within the interior pedal system (Figure 45). It is located between the accelerator pedal sensor and the control module, works by capturing the accelerator pedal signal, and transforms it. Many manufacturers offer similar functions via standard "sports buttons". The pedal box reduces the pedal travel necessary in order to reach a "throttle wide open" state (full throttle response). This allows the driver to exploit the full potential of the engines. The pedal assembly is constituted by a series of components including soundproof systems, metal inserts, pins, bumper, soft, pedals and pedal support, whose contribution on total pedal weight is about 25%. Pedal box support principal function is to fix the three pedals on the body. The production technology involves an injection-moulding machine: the polymer granules are fed through a hopper into the plasticizing cylinder of a press, are heated, softened and then injected into a mold cavity through which the component takes the shape. Through the thermoregulation system the workpiece is cooled, solidifies and is extracted from the cavity, at this point the machine is ready to begin a new production cycle.

Figure 45 - a) Reference vehicle, b) pedal system, c) pedal box support, d) pedal system design.



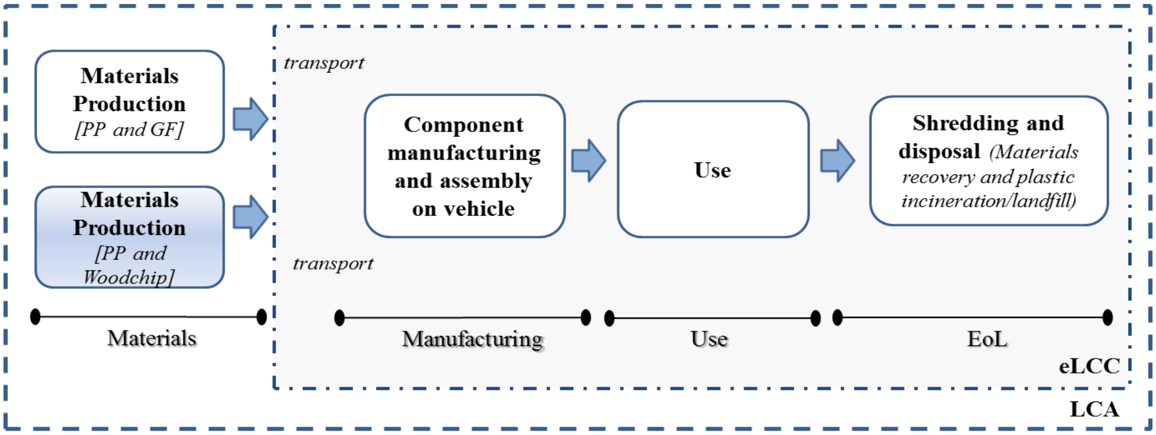
7.2.3 SYSTEM BOUNDARIES AND FUNCTIONAL UNIT

In this paragraph, the product system and the system boundaries are described. Regarding the system boundary, LCA is conducted by defining product systems as models that describe the key elements of physical systems. The system boundary defines the unit processes to be included in the system. Ideally, the product system is modelled in such a manner that inputs and outputs at its boundary are elementary flows. The choice of the elements of the physical system to be modelled depends on the goal and scope definition of the study. The two PBS options are analyzed as integrated within the interior pedal box system through all its life cycle, according to a "cradle to gate" approach, splitting it in the following macro-phases: materials, manufacturing, use, end of life and transport of each phase in between. For the present case study are considered the life cycle phase grouped according to:

- <u>materials</u> which includes raw materials extraction and their processing;
- <u>manufacturing</u> accounts for all the process involved within MM perimeter to produce the AIM;
- <u>transport</u> assess the impact attributed to all the shipments for the life cycle phases in between;
- <u>use</u> is based on component operation within the reference vehicle selected for a specific life time mileage;
- <u>end of life:</u> consists of all the process involved to recover/disposal of the materials (after vehicle dismiss) according to their typology.

Following Figure 46characterizes PBS life cycle phases for both scenarios. The two design solution differs for the: material and transport. The Functional Unit (FU) of the present analysis is one *automotive Pedal box support* integrated within the drivetrain system, supporting and housing all the instrumentation for vehicle use, to be mounted on Jeep Renegade 1,4 MultiAir Longitude 1368 cm3 (103 kW) car, for 150,000 km on 10 years.

Figure 46 – System boundaries pedal box support case study.



7.2.4 LCA ANALYSIS

Here is presented the LCA methodology application on PBS design solutions.

7.2.4.1 LIFE CYCLE INVENTORY (LCI)

In this sub-paragraph, data collection to quantify relevant inputs and outputs of the phases, which compose product life cycle, is described. Where possible process parameters (materials and energy flows) were obtained by direct measurements on industrial processes and/or estimation; in the others cases, assumptions from GaBi 6.115 processes database have been used. In Table 23 and Table 24 a description of modalities used to collect data is reported. The materials compositions and production are grouped with the reference of Gabi datasets and data quality. The use stage covers the operation of the PBS integrated within the pedal box system of the vehicle selected. It reflects the fuel consumption linked to the mass during the life time of a vehicle. To calculate impact imputable to the component operation over the vehicle life time [150,000 km], it was used an analytical model proposed by (Koffler and Rohde-Brandeburger 2010) considering the parameters in Table 25. The EoL management options have been modelled according to the PBS materials composition to separate plastic from the vehicle drained under the form of wreck. Energy consumption calculation is based on the mass of the sub-component to be treated according to the EoL options to recover/dispose certain material typology. The End of Life modelling includes the environmental burdens of recycling processes and grants credits for the recycled/ recovered materials.

Table 23 – LCA data collection standard design solution [PP-30GF].

	Standard Design		
Life cycle phase	**Specification**	**Quantity** *(per FU)*	**Process** *(GaBi; ecoinvent)*
Materials	Polypropylene [PP]	0.68 kg	Polypropylene granulate
	Glass fibers	0.261 kg	Glass fibers [Minerals]
Logistic	Total segments distance travelled	2,040 km	Truck, Euro 5, 14 - 20t gross weight / 11,4t payload capacity
Manufacturing	Injection molding	1.65 kWh	Electricity grid mix (IT)
EoL	1) Shredding (within drained vehicle) → Materials separation → plastic landfill	0.147 MJ	Electricity grid mix (IT); plastic waste on landfill
	2) Shredding (within drained vehicle) → Materials separation → plastic incineration	0.147 MJ	Electricity grid mix (IT); Polyamide (PA) 6 GF30 in waste incineration plant

Table 24– LCA data collection innovative design solution [PP-45WC].

	Innovative Design		
Life cycle phase	**Specification**	**Quantity** *(per FU)*	**Process** *(GaBi; ecoinvent)*
Materials	Polypropylene [PP]	0.447 kg	PP-NF45 *[granular]*[38]
	Woodchip	0.365 kg	
Logistic	Total segments distance travelled	3,040 km	Truck, Euro 5, 14 - 20t gross weight / 11,4t payload capacity
Manufacturing	Injection molding	1.59 kWh	Electricity grid mix (IT)
EoL	1) Shredding (within drained vehicle) → Materials separation → plastic landfill	0.138 MJ	Electricity grid mix (IT); plastic waste on landfill
	2) Shredding (within drained vehicle) → Materials separation → plastic incineration	0.138 MJ	Electricity grid mix (IT); PP+ 45 Wood (WPC) in municipal waste incineration plant [MM]

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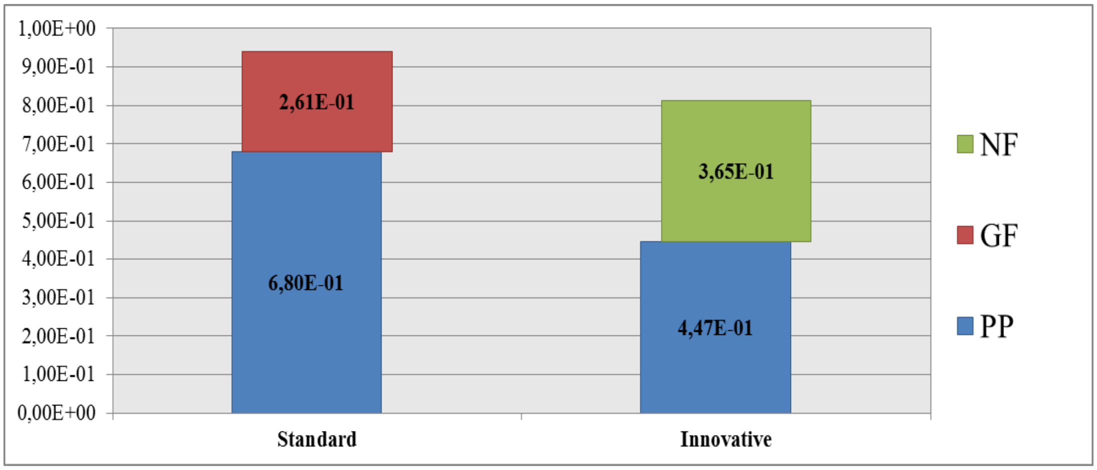
[38] Materials profile modeled (see chapter 5 paragraph 5.1.1.LCA in Magneti Marelli).

Table 25 - LCA data collection “Use phase”, vehicle technical data and model parameter for pedal box support.

Technical data referring to car model equipped with the pedal box support		
Vehicle technical characteristic	Model	1,4 MultiAir Longitude 1368 cm^3 (103 kW)
	Mass	1320
	Emission stage	EURO 6
	Motorway per-km CO_2 emission [g/km]	140
	Mixed consumption [l/100km]	6
Operation	Vehicle life time [km] - dm	150,000
Analytic model [NEDC]	Mass induced fuel consumption [l/100km*100kg] - FRV_PMR [Gasoline] - fm	0.15
Mass [m]	Vehicle equipped with standard pedal box support [kg]	0.869
	Vehicle equipped with innovative pedal box support [kg]	0.812
Fuel density	Gasoline [kg/dm^3]	0.74
Specific consumption [kg/kg fuel]	CO_2 emissions generated during the consumption of 1 kg of fuel [kg CO_2/Kg fuel] – f_{CO2}	3.12
	SO_2 emissions generated during the consumption of 1 kg of fuel [kg SO_2/Kg fuel] - f_{SO2}	0.00015

Figure 47 reports the materials breakdown and composition within the two design scenarios for the PBS. The main difference regards the plastic mechanical strength which for the standard is provided by GF, whereas for the innovative the natural fiber. The substitution with the new natural fibers reinforcement lead to a decrease of the use of a certain amount of polypropylene matrix. In fact, in standard design the plastic quantitative is about 0.6 kg, whereas in the innovative design composition is about 0.44 kg. Another material quantitative distribution is observed for the reinforcement, since for the standard the use of synthetic glass fibers is 0.26 kg; instead, in the innovative design the natural reinforcement necessary is 0.36 kg.

Figure 47 – Pedal box support materials breakdown for standard and innovative design.



Overall, in the modeling the assembly phases has been excluded, since the pedal box system since is a manual operation for which are not required further energy and/or materials expenditure.

7.2.4.2 LCA LIFE CYCLE IMPACT ASSESSMENT (LCIA)

In this section life-cycle environmental impact has been calculated on the basis of data gathered during the inventory; it has been done by applying *Classification* and *Characterisation* to LCI data according to ISO 14040 standard guidelines. The results of Life Cycle Impact Assessment are reported below; this has been obtained according to *CML 2001 Apr. 2016*regulations, the *Primary Energy Demand (PED)* category from renewable and non-renewable resources (gross cal. value) has been considered and the *Total freshwater consumption (including rainwater) [kg]*. Results are presented in Figure 48in a form to show, for each class of environmental impact, the contribution of each life cycle stage, on the total impact, for the two design solutions, whereas the total impact percentages delta [Δ%] for each impact indicator are reported in Table 26.

Figure 48 – LCIA Results for pedal box support for standard and innovative solution.

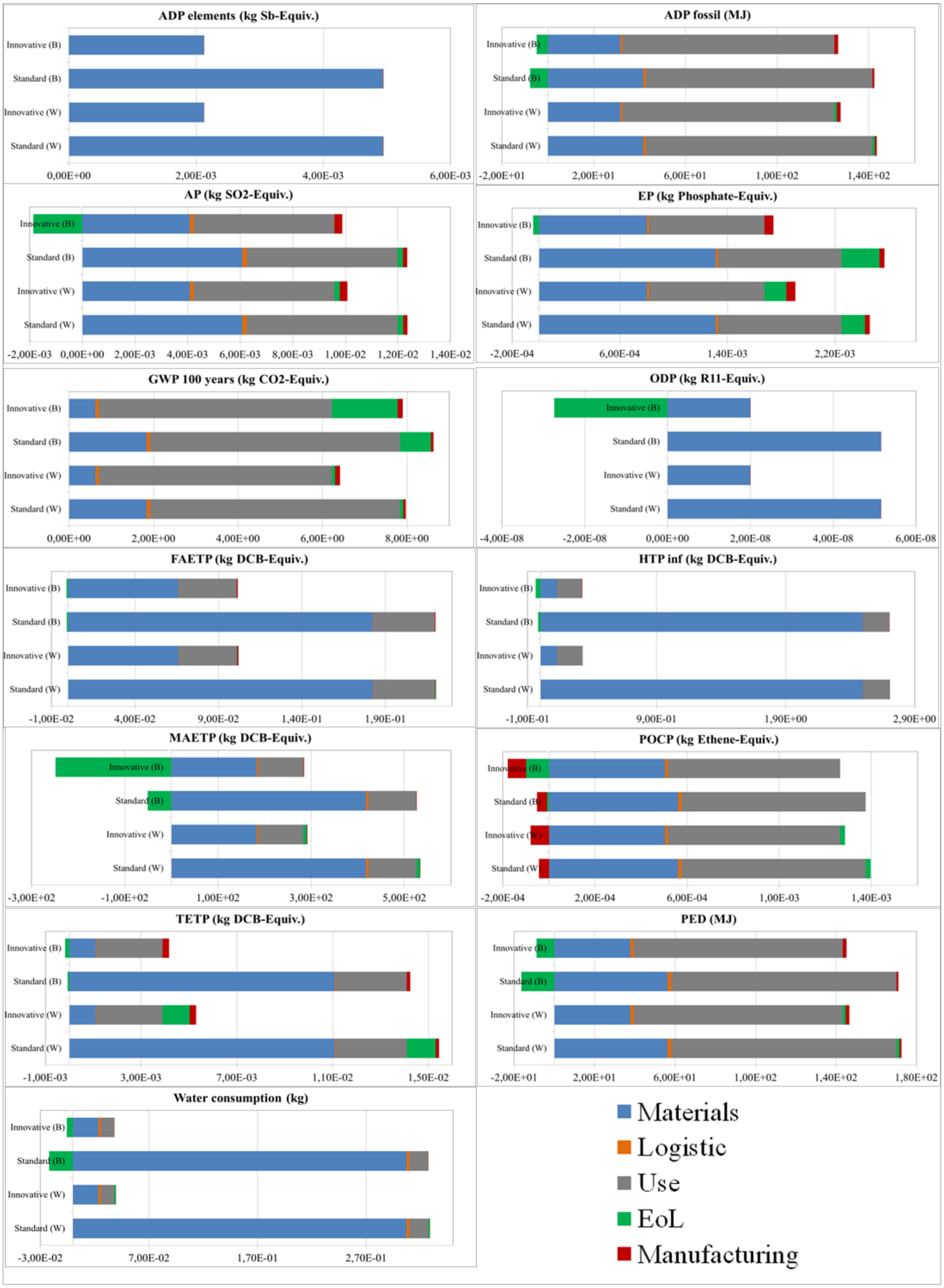


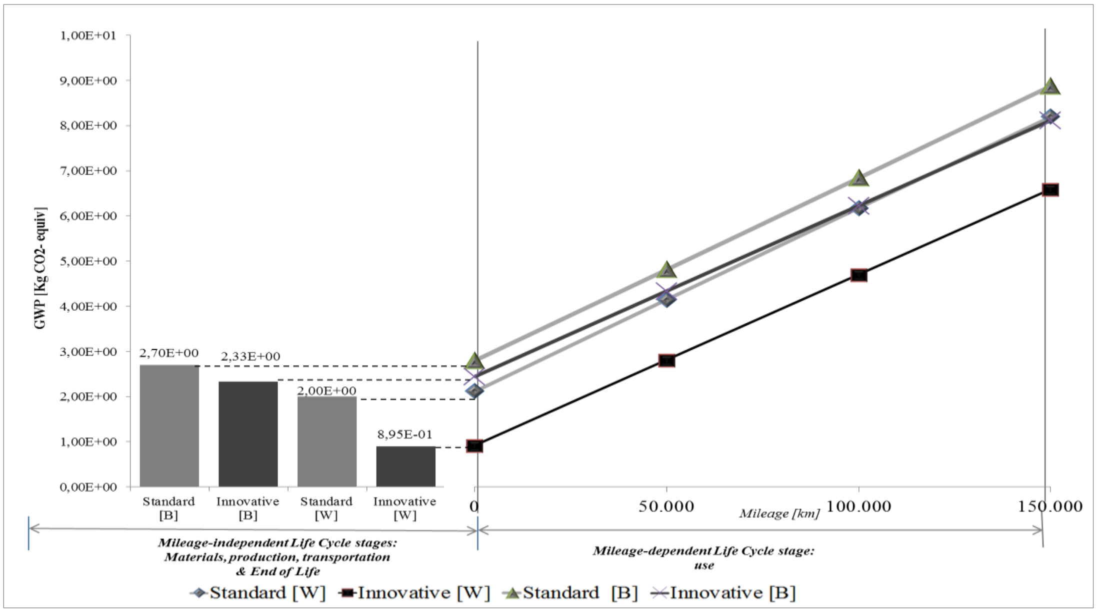
Table 26 –Pedal box support total impact percentage delta decrease (-) increase ( ), worst option (W) and best option (B).

Impact categories	**Δ% (W)**	**Δ% (B)**
CML2001 - Jan. 2016, Abiotic Depletion (ADP elements) [kg Sb eq.]	-133%	-133%
CML2001 - Jan. 2016, Abiotic Depletion (ADP fossil) [MJ]	-12%	-11%
CML2001 - Jan. 2016, Acidification Potential (AP) [kg SO2 eq.]	-23%	-54%
CML2001 - Jan. 2016, Eutrophication Potential (EP) [kg Phosphate eq.]	-29%	-51%
CML2001 - Jan. 2016, Freshwater Aquatic Ecotoxicity Pot. (FAETP) [kg DCB eq.]	-116%	-118%
CML2001 - Jan. 2016, Global Warming Potential (GWP 100) [kg CO2 eq.]	-24%	-9%
CML2001 - Jan. 2016, Human Toxicity Potential (HTP) [kg DCB eq.]	-731%	-844%
CML2001 - Jan. 2016, Marine Aquatic Ecotoxicity Pot. (MAETP) [kg DCB eq.]	-83%	-1220%
CML2001 - Jan. 2016, Ozone Layer Depletion Potential (ODP) [kg R11 eq.]	-158%	791%
CML2001 - Jan. 2016, Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	-12%	-22%
CML2001 - Jan. 2016, Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	-192%	-255%
Primary energy demand from ren. and non-ren. resources (gross cal. value) [MJ]	-18%	-13%
Total water consumption [kg]	-732%	-843%

GHG EMISSIONS BREAK-EVEN

Figure 49illustrates the GHG emissions of CO_2 over the life cycle contribution of the standard and innovative PBS considering worst [W] and best [B] scenario. The total amount is separated according to static attribution, as a sum of the total emissions occurred during the upstream and downstream activities (materials extraction and production, logistic, component manufacturing and EoL) with reference of the component operational use. Overall are presented four scenarios considering the EoL differentiation as worst option [W] considering plastic landfill and, on the contrary the case where plastics are incinerated [B]. The separation among the LC contribution is due to the fact that, CO2 emissions are directly dependent on component use, in fact the more the vehicle runs the more emissions are generated. The highest emissions are attributed to the heaviest component considering the plastic incineration options, wherease the lowest emissions occurs in the worst scenario case for the lightest component. No break-even point is observable since the standard solution accounts for the highest amount of CO2 emissions from the very beginning.

Figure 49 – GHG break-even results for standard and innovative pedal box support design.



7.2.4.3 LCA INTERPRETATION

Here results are presented in such a way to calculate the total impact score, for each design solutions, differentiating each life cycle phase's contribution, according to the impact attributed to a specific life cycle category. Overall, from the bar charts we can see that the materials and use phases are the most impacting. Each impact indicator is representative for a specific environmental issue and is generally influenced by a specific portion of product life cycle. The indicators which are sensible to the material depletion are: ADPelements, ODP, HTP and water; from the bar charts can be observed the sharp decrease of the impacts due to the employment of a renewable material, which require a low amount of incomes in terms of energy and auxiliary materials. Following GWP, PED, AP, EP, POCOP and ADPfossil are influenced by use stage where are consumed fossil material (fuel) and are generated more harmful emissions from tailpipe. The component lightweighting lead to an impact decrease. Turning to the other remaining categories, especially toxicity, we can observe a sharp decrease due to the substitution of a natural material in replace of a synthetic. Overall, for all the environmental impact categories is observed a reduction with the innovative design scenario. NO sensible variation can be perceived between the selections of the EoL management with the exception of GWP indicator, ODP and MAETP. The Manufacturing, Logistic and EoL categories present a minor contribution to the total components of components life cycle impact. Despite the negligible effect, it is important to underline the slight increase of logistic impact on the innovative design due to the increase of material distance travelled; whereas the reduction of manufacturing load is due to the decrease of energy expenditure with respect of component production.Regarding automotive industry, particular attention should be given to the control of the GHG emissions, since among others sectors, is the one that mostly contribute to their generation, especially during vehicle use. In light of this regard is provided the GHG emissions breakeven (Figure 49). What came out is that according to the 4 scenarios options the less emissions are allocated to the lightweight solution for Landfill options. In fact, in the incineration phase the disadvantage category is the GWP, since are generated emissions in the recovery process for energy production; apart from that the incineration should be preferred to landfill anyway for other numerous advantages.

7.2.5 ENVIRONMENTAL LIFE CYCLE COSTING

The following section describes the eLCC analysis of the PBS case study.

7.2.5.1 LIFE CYCLE INVENTORY [LCI]

The unit costs are given in Table 27 and according to what described in CHAPTER 5 (paragraph 5.1.2 *LCC methodology in Magneti Marelli*). Regarding the environmental eLCC the total cost is attributed from conventional LCC with the addition of the cost derived by the CO_2 emissions generated during component LC (accounting materials, manufacturing, logistic, EoL and use over 150,000 kilometers of use) and their damage cost [€/kg emissions]. The Clean Vehicles Directive 2009/33 /EC, provide valuations of specific environmental damage cost. CO_2 emissions were already calculated from LCA analysis.

Table 27– LCC inventory pedal box support standard and innovative design solutions.

Standard Design			
Life cycle phase	**Flow (*per FU)**	**Unit cost**	**Source**
Transports	Transports (fuel and driver) per km	1.1 €/km	*Primary data*
	Item quantity	0.869 kg/FU	
	Distance travelled	2,030 km	
	Truck gross weight	20 t	
	Truck payload	11.4 t	
Manufacturing	Electricity	0.12 €/kWh (average European)	*Eurostat, 2018*
Use	Gasoline	1.46 €/litre (avg European price)	*IEA, 2018*
	CO_2 emissions cost	4.00 x 10^{-5} €/gCO_2	*European Commission*
EoL	Electricity	0.12 €/kWh (average European)	*Eurostat, 2018*
	Plastic disposal [Worst case]	0.1 €/kg	*Primary data*

Innovative Design			
Life cycle phase	**Flow (*per FU)**	**Unit cost**	**Source**
Transports	Transports (fuel and driver) per km	1.1 €/km	*Primary data*
	Item quantity	0.812 kg/FU	
	Distance travelled	2,030 km	
	Truck gross weight	20 t	
	Truck payload	11.4 t	
Manufacturing	Electricity	0.12 €/kWh (average European)	*Eurostat, 2018*
Use	Gasoline	1.46 €/litre (avg European price)	*IEA, 2018*
	CO_2 emissions cost	4.00 x 10^{-5} €/gCO_2	*European Commission*
EoL	Electricity	0.12 €/kWh (average European)	*Eurostat, 2018*
	Plastic disposal [Worst case]	0.1 €/kg	*Primary data*

7.2.5.2 eLCC IMPACT ASSESSMENT [LCIA]

In Table 28 are presented the total cost attributable to the PBS from MM perspective, internalizing the cost attributable to user during vehicle use and EoL management to recover and/or disposal the relative materials. Economic assessment results are described according to the following cost categories: manufacturing, transports, use and end-of-life. The perspective used in the analysis could mainly give information to the producer for the evaluation of the innovative convenience of the adoption of the innovative design. Only the costs of materials and sub-components acquisitions have been excluded. Despite the only difference regards the cost of acquisition of the GF-compound with NF-compound.

The calculation of each contribution has been accomplished following the rules reported in CHAPTER 5 (paragraph 5.1.2 LCC methodology in Magneti Marelli) and considering the following assumptions:

- for transport considering the logistic management along PBS LF, therefor considering fuel expenditure and driver salary;
- for manufacturing the cost attributable to each production item considering the contribution of energy expenditure, which is the only variation among standard and innovative costs scenario;
- for use the total fuel consumption during vehicle life-time mileage of 150,000 km attributable to each component, multiplied by the average European cost of gasoline fuel, in addition the calculation takes into account the discount method which results are illustrated in Figure 49;

- for EoL the cost attributable to the disposal and/or recovery of each material flow within the dismantle line for materials recovery.

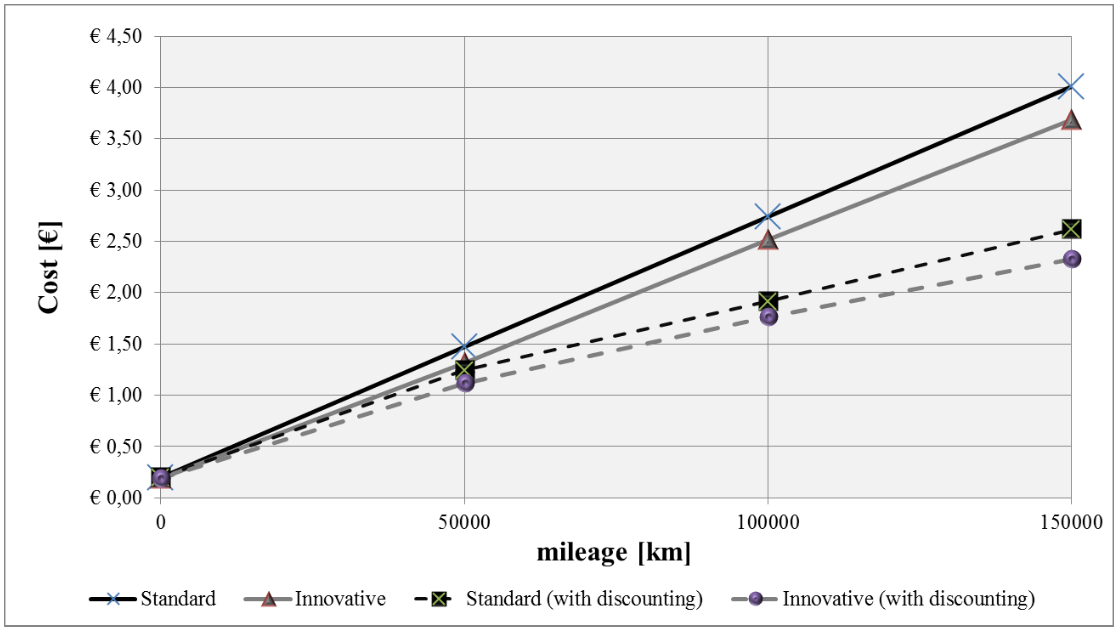
The eLCC results in a total cost of standard solution of 4, 19 € and of the innovative of 3, 49 €.

Table 28 - eLCC results pedal box support.

Reference	**Flow**	**Standard unit cost [W] [€/FU]**	**Innovative unit cost [W] [€/FU]**	**Standard unit cost [B][€/FU]**	**Innovative unit cost [B] [€/FU]**
Transport	Distance travelled	*€ 0,098*	*€ 0,184*	*€ 0,098*	*€ 0,184*
Manufacturing	Production	*€ 0,20*	*€ 0,19*	*€ 0,20*	*€ 0,19*
Total cost (MM perspective)		***€ 0,30***	***€ 0,37***	***€ 0,30***	***€ 0,37***
Use	Fuel (150.000 km)	*€ 3,81*	*€ 3,49*	*€ 3,81*	*€ 3,49*
	Externalities	*€ 0,00032*	*€ 0,00026*	*€ 0,00035*	*€ 0,00032*
Total cost (user perspective)		***€ 3,81***	***€ 3,49***	***€ 3,81***	***€ 3,49***
EoL	Materials separation	*€ 0,0049*	*€ 0,0046*	*€ 0,0049*	*€ 0,0046*
	Materials recovery/dispose	*€ 0,087*	*€ 0,0812*	*€ 0,087*	*€ 0,0812*
Total life cycle cost[€/FU]		***€ 4,19***	***€ 3,95***	***€ 4,19***	***€ 3,95***

Figure 50 depicts the fuel consumption cost break-even analysis over the vehicle 150,000 km mileage of use. A sensitivity analysis reporting a comparison among discounting and non-discounting calculation has been accomplished. From the line chart could be observed a break-even point since the economic convenience of the innovative PBS production starts from production stage.

Figure 50 – Fuel cost break-even pedal box support.



7.2.5.3 eLCC RESULTS INTERPRETATION

From the results reported in Table 28 could be distinguished the contribution of the total cost attributable to the PBS life cycle. As can be seen the most outgoings regard the use stage, where the cost account for fuel expenditure. However, different result could be sensitive from the perspective considered. From MM perspective, the implementation of the innovative solution means a production cost increase of 27% principally due to the logistic attribution. The increase of the total distance travelled (due to the distance of materials supplier) negatively impact cost invoice, whereas the decrease of energy expenditure for manufacturing activities bring to the reduction of MM manufacturing cost of 4%. A slight fee decrease regard EoL disposal due to the low materials incomes to be processed. Nonetheless, the use phase cost counterbalances the negative cost impact due to the logistic running. Thus, the implementation of the lighter innovative materials decrease the total cost over each LC dimensions of 6%, with more benefits related to the user perspective.

7.3 BRAKEPEDAL

This project focuses on the environmental impact assessment analysis between *two different materials and technology* for the production of a specific automotive component: a brake pedal (hereafter BP). The method adopted is a combination of a *Life Cycle Assessment (LCA)* and a *Life Cycle Costing (LCC)* as a part of Life Cycle Sustainability Assessment (LCSA) analysis.

The purpose is to make evidence on which of the two materials profile cause the environmental impact and economic expenditure, considering the full product life cycle. For this purpose, the perimeter of the analysis include all the phases upstream and downstream of the MM production stage, performing in this way what is so called “cradle to grave” approach analysis.

Overall, the main goals of the project are:

- verify applicability of LCA and LCC as a supporting tool to “identify the main sustainability hotspots in the product life cycle - especially regarding its technology function during its operation on the vehicle - therefore guide strategy development” and provide elements for production decisions for BP production;
- develop data collection on environmental and economic impact of the different production technologies regarding the manufacturing of a BP;
- create a model for the environmental assessment of a specific material;
- provide guidance on different product design proposals based on environmental and economic impact point of view.

7.3.1 GOAL AND SCOPE DEFINITION

The scope of the present study is to assess the environmental and economic impacts of a Brake Pedal in view of “cradle to grave” approach. The main driver taken into account for improvement is the *lightweighting* effect due to the lowering density of the innovative material for the production of the new design solution. The present analysis can be used to supply sustainability information to improve product performances in terms of:

- life cycle perspective to assess a balance among environment and economic point of view;
- quantifying energy and resource intensive processes and minimizing their impact;
- identifying cost savings for the manufacturer and consumer;
- developing an evaluation of impacts and risks to human health and environment from the local to national and global scales.

In order to assess the performance of the product with the employment of the innovative material, a comparative LCA and LCC analysis between two different design solutions, has been accomplished. The technical description and differences between the two scenarios are reported in Table 29 and materials breakdown data of the two design solutions are reported in Figure 51. The consequences of material variations are: sub-components and logistic variation.

Table 29 - Technical data of brake pedal design solutions.

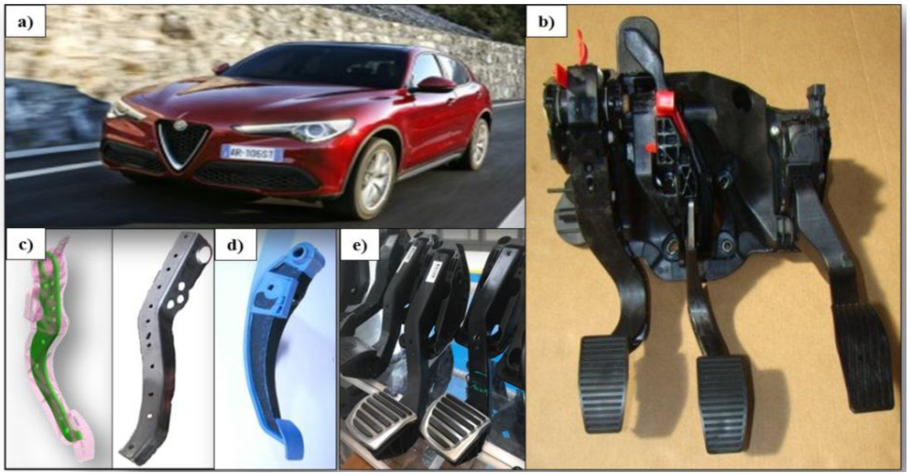
Features	Standard	Innovative	Variation
Weight (kg)	1.015	0.552	45% weight reduction
Part/s	Metal insert [Stainless steel (Fe420)]	-	*Metal insert* elimination
	compounding [Polyamide 6 reinforced with glass fibers (*PA 66 GF60)*]	compounding [Polyamide 6.6 reinforced with carbon and glass fibers (*PA 66-CF15-GF10)*]	Reinforced filler change
Production technology	Thermoforming -> Injection Molding	Injection Molding	Invariant with shortening of time cycle due to the elimination of *thermoforming* process and shortening of *injection molding*

7.3.2 COMPONENT DESCRIPTION

The brake pedal, depicted in Figure 51 takes part in the vehicle control system; it is located and integrated within pedal system through a support. The brake pedal is a lever used to decelerate vehicle speed, which is controlled and modulates by the pressure exerted by the driver's control. The standard brake pedal consists of two different parts, a metallic insert and an overmoulded thermoplastic material, in order to obtain a single pedal structure (Figure 51). The metallic insert is produced using ferrous alloy, whereas the thermoplastic material is glass fibers-reinforced polyammide.

The innovative brake pedal (Figure 51) is produced as one-single unitary structure. The functional requirements are obtained through the substitution of the metals part and the thermoplastic materials with one single innovative material, which perform the same mechanical and thermal resistance requirement of the standard material, bringing the advantage of decreasing the brake pedal weight (~45%). This goal is possible through the replace of the metallic insert using one only composite material for the whole pedal. The innovative material is a thermoplastic short-carbon-fibers-GF-reinforced composite (PA66 15% CF 10% GF). The variation of materials did not lead to a geometry design variation of the component as well as for the production technology. The difference between the two design solutions regards the numbers of the components that take parts in the production of the product, since the metallic insert is removed in the innovative design option; there is a simplification of the total number involved. In addition, the change of material and the sub-components simplification, lead to a reformulation of the transport management supply chain. The manufacturing phase for both design solutions, consists of one single step operation, (with the exception of the standard product where the metallic insert is co-molded) performed with injection molding. The materials in granular form are inserted inside the hopper and therefore is heated, worked, cooled and the final component (brake pedal) is expelled.

Figure 51 – a) Reference vehicle, b) brake pedal system, c) section standard brake pedal and metal insert, d) innovative brake pedal e) brake pedal as produced.



7.3.3 SYSTEM BOUNDARIES

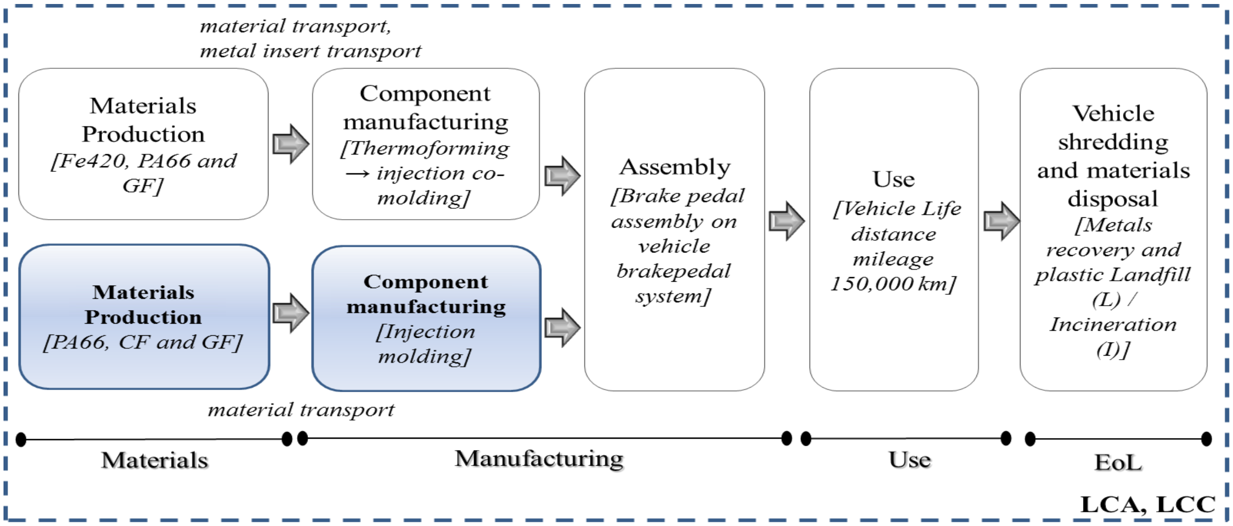
In this paragraph, the product system and the system boundaries are described. Regarding the system boundary, LCA is conducted by defining product systems as models that describe the key elements of physical systems. The system boundary defines the unit processes to be included in the system. Ideally, the product system should be modelled in such a manner that inputs and outputs at its boundary are elementary flows. However, resources need not be expended on the quantification of such inputs and outputs that will not significantly change the overall conclusions of the study.

The brake pedal life cycle is divided into four phases:

- Materials, which includes raw materials extraction and their processing.
- Manufacturing phase consists of the collection of all data (energy, auxiliary consumptions…etc.) of related to the production of the component.
- Transportation of materials to the plant of components manufacturing and transportation of the components to the plant of assembly on the pedal system of the vehicle.
- Use that includes: fuel production and tailpipe emissions.
- End of Life consists of all the process involved to recover/disposal of the materials (after vehicle dismiss) according to their typology.

Following Figure 52 characterizes brake pedal life cycle phases for both scenarios. The two design solution differs for the material, end-of-life and transport of these phases in between". The two brake pedals are analyzed as integrated within the pedal system through all its life cycle. The Functional Unit (FU) of the present analysis is an automotive brake pedal for the vehicle use, to be mounted on Alfa Romeo Stelvio 280 HP, gasoline engine, with a life-distance of 150,000 km for 10 years.

Figure 52 – Brake pedal system boundary case study.



7.3.4 LCA ANALYSIS

Here is presented the LCA methodology application on AIM design solutions.

7.3.4.1 LIFE CYCLE INVENTORY (LCI)

In this sub-paragraph, data collection to quantify relevant inputs and outputs of the phases, which compose product life cycle, is described. Where possible process parameters (materials and energy flows) were obtained by direct measurements on industrial processes and/or estimation; in the others cases assumptions from GaBi 6.3 processes database have been used. Below a description of modalities used to collect data is reported in Table 30 and Table 31. The use stage covers the operation of the brake pedal integrated within the pedal unit of the vehicle selected [Alfa Romeo Stelvio 280 HP, gasoline]. It reflects the fuel consumption linked to the mass weight during the vehicle operation over a life span of 150,000 km. It is assumed, that the brake pedal unit does not require exchange or maintenance in the considered life span.

To calculate the environmental impact imputable to the brake pedal during the vehicle life time, it was used an analytical model proposed by (Koffler and Rohde-Brandeburger 2010).

For the modeling of the use phase a reference vehicle with the same technical characteristics of the car on which the brake pedal is installed has been selected and reported in Table 32.

Following the flowchart in ISO 22628 three EoL management options have been modeled according to the brake pedal materials composition to recover:

- *Ferrous materials*: shredding → aeraulic separation → magnetic separation [to separate steel];
- *Plastics*: from metal recovery process → fluff treatment in press machine [to obtain compacted fluff].

The energy consumption calculation is based on the mass of the materials to be treated according to the EoL options. The End of Life modelling includes the environmental burdens of recycling processes and grants credits for the recycled/ recovered materials. Considering the management of plastic end of life options, two different scenario has been considered; the first regard the case where plastic is sent to the landfill (worst scenario), whereas in the best option the plastics material are destined to the incineration treatment (best scenario).

Table 30 – LCA data collection standard brake pedal design.

	Standard Design		
Life cycle phase	**Specification**	**Quantity** *(per FU)*	**Process** *(GaBi; ecoinvent)*
Materials	Stainless steel [Fe420]	0.44 kg	Stainless steel cold rolled coil (430) [Metals] and Steel sheet deep drawing
	Polyamide 6 [PA 6]	0.23 kg	Polyamide 6 Granulate (PA 6) [Plastics]
	Glass fibers [GF]	0.345 kg	Glass fibers [Minerals]
Logistic	Total segments distance travelled	1,505 km	Truck, Euro 5, 14 - 20t gross weight / 11,4t payload capacity
Manuf.	Injection molding	0.575 kWh	PP injection moulding [Plastics Europe]; Electricity grid mix (IT)
EoL	1) Shredding (within drained vehicle) → Materials separation → Metals recovery and plastic landfill	0.044 kWh	EU-28: Plastic waste on landfill; Electricity grid mix (IT)
	2) Shredding (within drained vehicle) → Materials separation → Metals recovery and plastic incineration	0.044 kWh	Polyamide (PA) 6 GF30 in waste incineration plant; Electricity grid mix (IT)

Table 31 - LCA data collection innovative brake pedal.

	Innovative Design		
Life cycle phase	**Specification**	**Quantity** *(per FU)*	**Process** *(GaBi; ecoinvent)*
Materials	Polyamide 6.6 [PA 6]	0.414 kg	Polyamide 6 Granulate (PA 6) [Plastics]
	Carbon Fibers [CF]	0.0828	Carbon Fiber (CF; from PAN; standard strength)
	Glass fibers [GF]	0.0552 kg	Glass fibers [Minerals]
Logistic	Total segments distance travelled	815 km	Truck, Euro 5, 14 - 20t gross weight / 11,4t
Manuf.	Injection molding	0.552 kWh	PP injection moulding [Plastics Europe]; Electricity grid mix (IT)
EoL	1) Shredding (within drained vehicle) →Materials separation → plastic landfill/incineration	0.026 MJ	Plastic waste on landfill/ Polyamide (PA) 6 GF30 in waste incineration plant;; Electricity grid mix (IT)

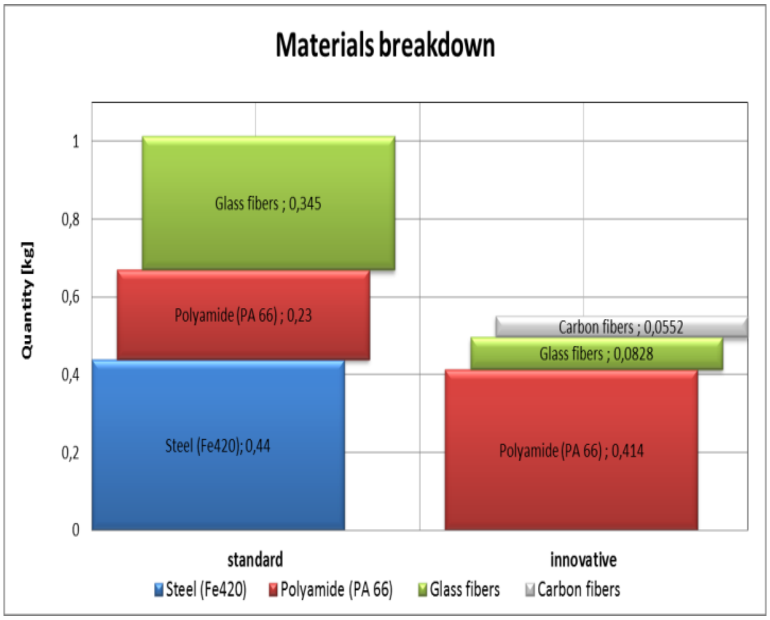
Table 32 – LCA data collection "Use phase", vehicle technical data and model parameter for brake pedal.

Technical data referring to car model equipped with the brake pedal		
Vehicle technical characteristic	Model	Alfa Romeo Stelvio 280 HP, gasoline (206 kW)
	Mass	1650
	Emission stage (e.g. EURO5)	6
	Motorway per-km CO_2 emission [g/km]	149
	Mixed consumption [l/100km]	5.3
Operation	Vehicle life time [km] - dm	150,000
Analytic model [NEDC]	Mass induced fuel consumption [l/100km*100kg] - FRV_PMR [Gasoline] - fm	0.15
Mass [m]	Vehicle equipped with standard pedal box support [kg]	1.015
	Vehicle equipped with innovative pedal box support [kg]	0.552
Fuel density	Gasoline [kg/dm^3]	0.74
Specific consumption [kg/kg fuel]	CO_2 emissions generated during the consumption of 1 kg of fuel [kg CO_2/Kg fuel] – f_{CO2}	3.12
	SO_2 emissions generated during the consumption of 1 kg of fuel [kg SO_2/Kg fuel] - f_{SO2}	0.00015

In the modeling of the BP life cycle, the packaging consumption has been excluded since materials are always recovered for the same purposes.

In Figure 53 below is reported the materials breakdown according to their composition and weight contribution on standard and innovative design. The two components design share the PA66 and GF materials typology, with different quantity. What is different is the lack of metals in the innovative and the presence of low amount of CF.

Figure 53 – Materials composition breakdown for the two PB design solutions.



7.3.4.2 LIFE CYCLE INVENTORY (LCI)

In this section, thelife cycle environmental impact has been calculated on the basis of data gathered during the inventory; it has been done by applying *Classification* and *Characterisation* to LCI data according to ISO 14040 standard guidelines. The results of Life Cycle Impact Assessment are reported below; this has been obtained according to *CML 2001 Apr. 2016*regulations, the *Primary Energy Demand (PED)* category from renewable and non-renewable resources (gross cal. value) has been considered and the *Total freshwater consumption (including rainwater) [kg]*. Results are presented in Figure 54 and Figure 55 in a form to show, for each class of environmental impact, the contribution of each life cycle stage, on the total impact, for the two design solutions, whereas the total impact percentages delta [Δ%] for each impact indicator are reported in Table **33**.

Figure 54 – LCIA results for brake pedal design solutions and EoL option according to the CML 2001 Apr. 2016 impact categories.

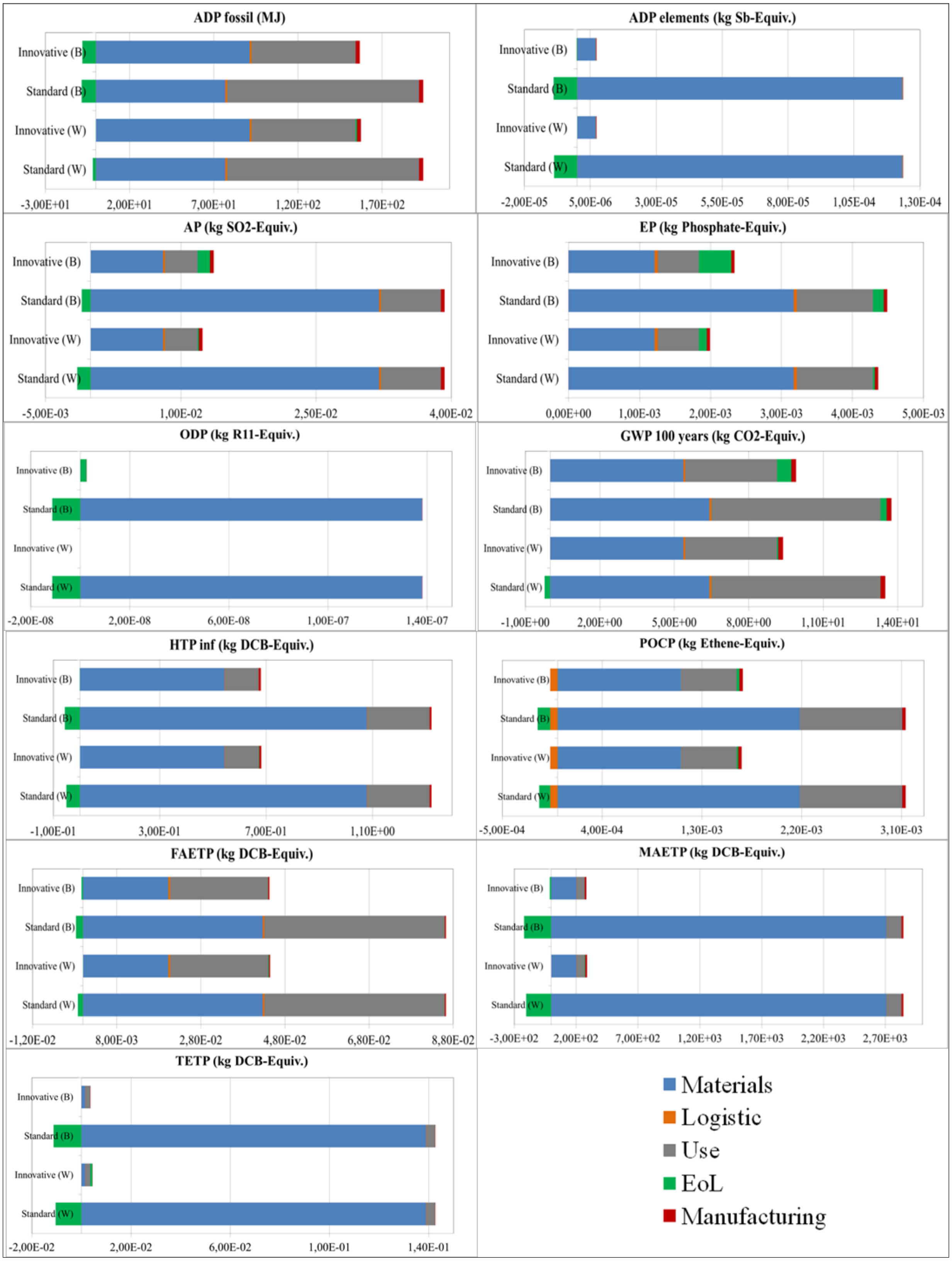


Figure 55 - LCIA results for brake pedal design solutions and EoL option according to the PED and Water Depletion impact categories.

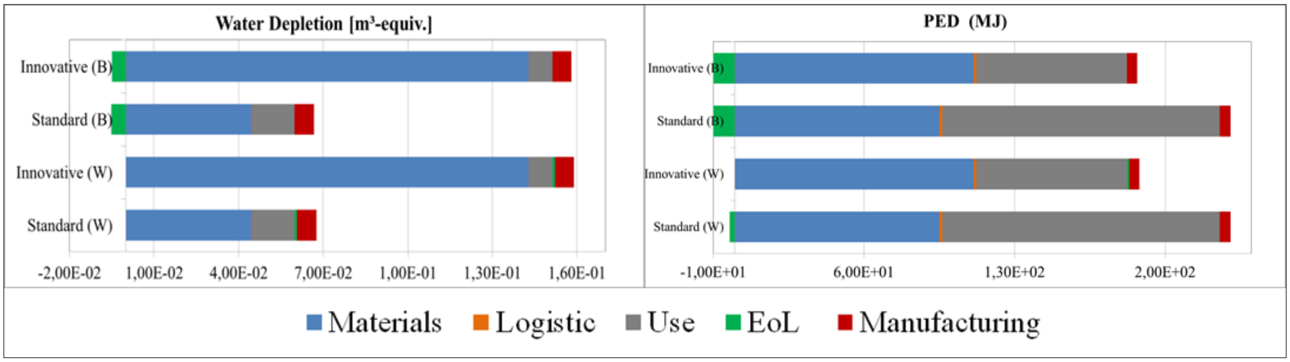


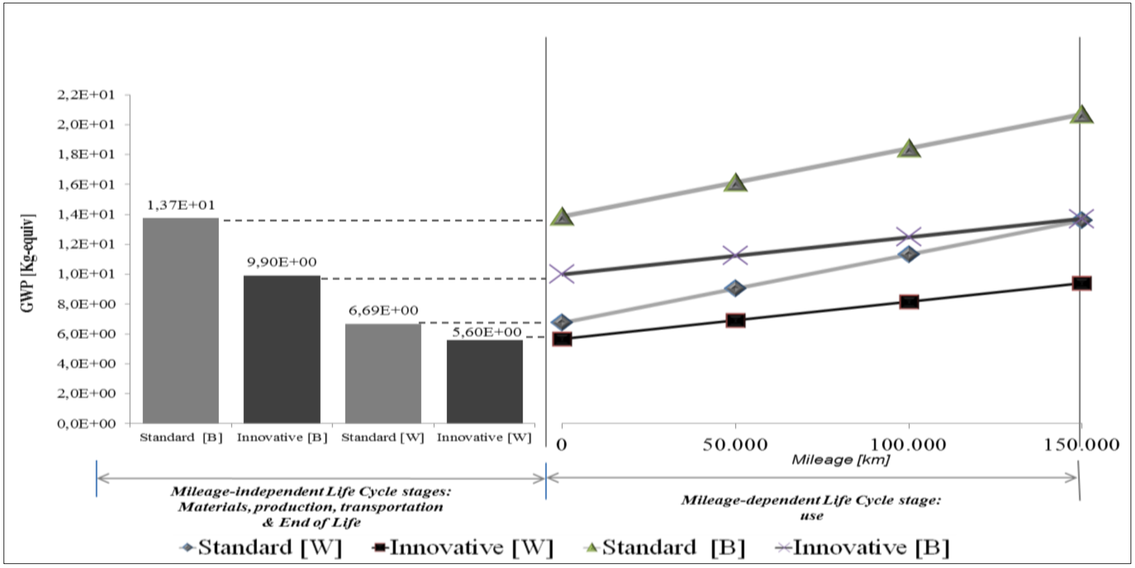
Table 33 - Brake pedal Total impact percentage delta decrease (-) increase ( ), worst option (W) and best option (B).

Impact categories	**Δ% (W)**	**Δ% (B)**
CML2001 - Jan. 2016, Abiotic Depletion (ADP elements) [kg Sb eq.]	-94%	-94%
CML2001 - Jan. 2016, Abiotic Depletion (ADP fossil) [MJ]	-18%	-20%
CML2001 - Jan. 2016, Acidification Potential (AP) [kg SO2 eq.]	-67%	-64%
CML2001 - Jan. 2016, Eutrophication Potential (EP) [kg Phosphate eq.]	-54%	-48%
CML2001 - Jan. 2016, Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	-48%	-48%
CML2001 - Jan. 2016, Global Warming Potential (GWP 100 years) [kg CO2 eq.]	-29%	-28%
CML2001 - Jan. 2016, Human Toxicity Potential (HTP inf.) [kg DCB eq.]	-46%	-46%
CML2001 - Jan. 2016, Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	-89%	-90%
CML2001 - Jan. 2016, Ozone Layer Depletion Potential (ODP) [kg R11 eq.]	-100%	-98%
CML2001 - Jan. 2016, Photochemical. Ozone Creation Potential (POCP) [kg Ethene eq.]	-46%	-46%
CML2001 - Jan. 2016, Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	-97%	-97%
Primary energy demand from ren. and non-ren. resources (gross cal. value) [MJ]	-47%	-33%
Total freshwater consumption (including rainwater) [kg]	-63%	-62%

GHG BREAK-EVEN ANALYSIS

In order to assess the consumption of GHG emissions generated along component life cycle, the following break-even analysis is reported in Figure 56. The reference is two brake pedals for the fourth scenarios: standard and innovative brake pedal considering incineration [B] and landfill [W]. The graph show the emissions generated upstream and downstream of the vehicle use (static contribution) and the dynamic emissions generated during component operation within the vehicle selected (Alfa Romeo Stelvio) along different vehicle life-distance mileage. The line chart displays the variation of CO_2 emissions generated during components use within the vehicle for a life span of 150,000 km. The lowest level (axis corresponded to 0 km) is referred to the emissions generated upstream and downstream (materials, logistic, manufacturing and end of life phases contribution). According the graphs, the most sensible variation regarding the CO_2 emissions are attributable to the operation of the component within the vehicle selected. The more the vehicle runs and the more discrepancy are observed, considering EoL worst case example: starting with 12% before vehicle use to the 29%. Instead, considering the EoL best case: starting with 11% before vehicle use to the 25%. For both cases, considering only the dynamic variation linked to the vehicle operation, after 150,000 km the discrepancy observed is about 46%, in line with component mass decrease.

Figure 56 – GHG emissions break-even for brake pedal scenarios.



7.3.4.3 LCA INTERPRETATION

The lightweight effect, due to the elimination of the heavy metallic component with the substitution of a lower material density (PA66 15% CF 10% GF) causes an overall impact decreases ranging between 18% and 99%. The most outstanding reduction (from 84% to 99%) regards the following impact categories: ADP elements, ODP, TETP and MAETP, mainly attributable to the material impact decrease. Overall, the two major contributions, in terms of life cycle phase incidence, are attributed to the materials production (material phase category) and component operation (use category). Each impact indicator is representative for a specific environmental issue and it is generally influenced by a specific portion of product life cycle. In the specific case regarding the vehicle operation (use), the impact categories affected are respectively: GWP, ADP fossil, POCP and PED; consequently, the decrease of component weight lead to reduction of the impact of the above categories, with major repercussion linked to the use category. The Manufacturing, Logistic and EoL categories present a minor contribution to the total components of components life cycle impact. Despite the negligible effect, it is important to underline the slight advantages that the innovative design brings in terms of transport reduction, due to the reduction of transport distance. With regard to the EoL contribution, the standard solution represent the less impacting profile, both considering worst and best scenario, since the metal insert is easily recoverable and present a major credit profile.

Moreover, the process of recovery of metals is less impacting, since the process of plastic occurs downstream to the ferrous parts recovery; this is translated in major energy to recover the plastic. Nonetheless, plastic worsen the effect on EoL, not only for the recovery operations, but mostly because is commonly disposed in landfill, rather than been recovered through incineration process. In fact, when best scenario is assumed (plastic incineration) the discrepancy of the EoL impact between standard and innovative is sensibly reduced.

Considering the break-even graphs depicted in Figure 56 the most sensible variation regarding the GHG emissions are attributable to the operation of the component within the vehicle selected. The more the vehicle runs and the more discrepancy are observed. Sensible variations are observed if in the calculation of GHG is accounted the EoL contribution.

7.3.5 ENVIRONMENTAL LIFE CYCLE COSTING

The following section describes the eLCC analysis of the AIM case study.

7.3.5.1 LIFE CYCLE INVENTORY [LCI]

The unit costs are given in Table 34 and according to what described in CHAPTER 5 (paragraph 5.1.2 LCC methodology in Magneti Marelli). Regarding the environmental eLCC the total cost is attributed from conventional LCC with the addition of the cost derived by the CO2 emissions generated during component LC (accounting materials, manufacturing, logistic, EoL and use over 150,000 kilometers of use) and their damage cost [€/kg emissions].

The Clean Vehicles Directive 2009/33 /EC [30] provide valuations of specific environmental damage cost. CO2 emissions were already calculated from LCA analysis.

Table 34– LCC inventory brake pedal standard and innovative design solutions.

Life cycle phase	Flow (*per FU)	Unit cost	Source
Standard Design			
Material	Standard production	2.24 €/kg	*Primary data*
Transports	Transports (fuel and driver) per km	1.1 €/km	
	Item quantity (metallic insert)	0.44 kg	
	Distance travelled (km) (metallic insert)	1372	
	Item quantity (standard material)	0.575	
	Distance travelled (km) (standard)	133	
	Truck gross weight (ton)	13	
	Truck payload (ton)	9.3	
	Transports	1.1 €/km	
Manuf.	Electricity	0.12 €/kWh (average European)	*Eurostat, 2018*
	Electricity (injection molding)	0.575 kWh	*Primary data*
Use	Gasoline	1.46 €/litre (avg European price)	*IEA, 2018*
	CO_2 emissions cost	4.00×10^{-5} €/gCO_2	*EC*
EoL	Electricity	0.12 €/kWh (average European)	*Eurostat, 2018*
	Steel recovery *	0.19 €/kg	*Primary data*
	Plastic disposal [Worst case]	0.1 €/kg	
Innovative Design			
Material	Innovative solution	7.5 €/kg	*Primary data*
Transports	Transports (fuel and driver) per km	1.1 €/km	
	Item quantity (innovative)	0.55 kg	
	Distance travelled (km) (innovative material)	1230	
	Truck gross weight (ton)	13	
	Truck payload (ton)	9.3	
	Transports	1.1 €/km	
Manuf.	Electricity (injection molding)	0.552 kWh	
	Electricity	0.12 €/kWh (average European)	*Eurostat, 2018*
Use	Gasoline	1.46 €/litre (avg European price)	*IEA, 2018*
	CO_2 emissions cost	4.00×10^{-5} €/gCO_2	*EC*
EoL	electricity	0.12 €/kWh (average European)	*Eurostat, 2018*
	Steel separation	0.04 kWh/kg	*Primary data*
	Plastic separation	0.007 kWh/kg	
	Plastic disposal [Worst case]	0.1 €/kg	

7.3.5.2 LCC IMPACT ASSESSMENT [LCIA]

In Table 35 are presented the total cost attributable to the brake pedal from different perspective, internalizing the cost attributable to user during vehicle use and EoL management to recover and/or disposal the relative materials. Economic assessment results are described according to the following cost categories: materials, manufacturing, transports, use and end-of-life. 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 calculation of each contribution has been accomplished as reported below:

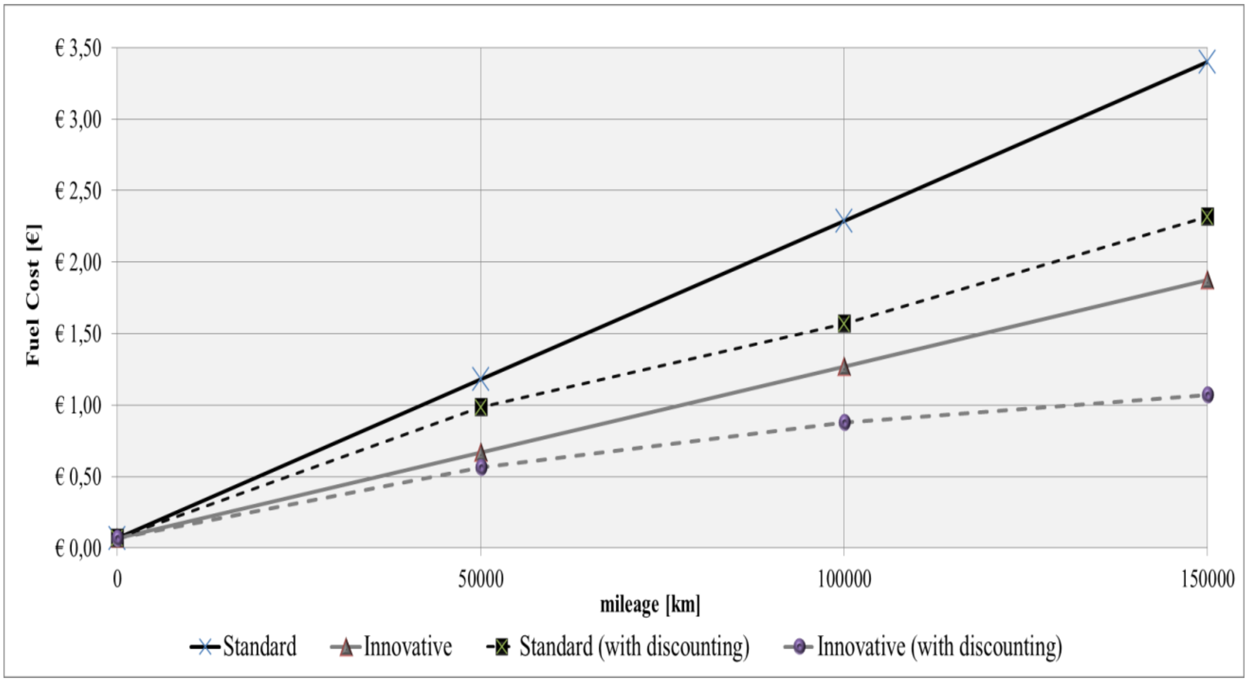
- for materials: the cost of acquisition from suppliers, with the exception of the metal part in the standard brake pedal which consider the acquisition of the metal item;
- for transport: the incidence of the cost per km multiplied by the total distance traveled and divided by truck payload capacity;
- for manufacturing: the cost attributable to each production item considering the contribution of direct labour and machine costs;
- for use: the total fuel consumption during vehicle life-time mileage of 150,000 km attributable to each component, multiplied by the average European cost of gasoline fuel;
- for EoL: the cost attributable to the disposal and/or recovery of each material flow within the dismantle line of vehicle.

Table 35 - eLCC results brake pedal.

Reference	Flow	Standard [€/FU]	Innovative [€/FU]
Material	Metal material	€ 0,68	
	Plastic material/s	€ 0,86	€ 3,08
Transport	Distance travelled	€ 0,13	€ 0,11
Manufacturing	Production	€ 0,069	€ 0,066
Total cost (MM perspective)		***€ 1,74***	***€ 3,26***
Use	Fuel (150.000 km)	€ 3,40	€ 1,88
	Externalities	€ 0,0005	€ 0,0004
Total cost (user perspective)		***€ 3,40***	***€ 1,88***
EoL	Materials separation	€ 0,005	€ 0,003
	Materials recovery/dispose	-€ 0,081	€ 0,055
Total life cycle cost		**€ 5,06**	**€ 5,20**

Figure 57depicts the fuel consumption cost break-even analysis over the vehicle 150,000 km mileage of use. A sensitivity analysis reporting a comparison among discounting and non-discounting calculation has been accomplished. From the line chart could be observed a break-even point since the economic convenience of the innovative BP production starts from production stage.

Figure 57 – Fuel cost break-even brake pedal.



7.3.5.3 eLCC INTERPRETATION

The economic results are presented (Table 35) according to the following categories: materials, transport, manufacturing, use and EoL. To obtain the total cost it was necessary to combine the LCA inventory with the once regarding LCC data collection. From the results could be seen that, for both products scenario, the materials acquisition and fuel quantity for vehicle use represent the greatest impact, followed by manufacturing; whereas the cost attributable to the EoL management has a negligible impact. The main difference of the two scenarios regards the cost of the materials; in fact, the innovative material present a cost of acquisition more than doubled compared to the standard one, which include also the cost of metallic insert. Despite that relevant difference, the other cost account presents a lower value, balancing in this way the material cost acquisition. Overall the total cost attributed to the current production is 5, 06 € per item, whereas for innovative proposal 5, 2 € per item, increasing the 2% the initial price. Overall, the total cost attributable to the innovative design proposal, reveals to have less cost impact, with the exception of the material acquisition. The trade-off between materials cost and manufacturing depends on where the consistent cost saving during use (46%) manage to counterbalance the material cost increase of the innovative material. From Magneti Marelli perspective, the cost of the production decrease about 16%, without considering the cost of acquisition of the metallic insert and 18% for transport operation. Nevertheless, the adoption of the innovative solution still presents a challenge since the cost of material acquisition is an external barrier for the company. The convenience is in favour of the user during vehicle operation, the lightweighting results in a total fuel saving of 46%.

7.4 SUSPENSION ARM

This project focuses on the environmental impact assessment analysis between *different materials and alternatives application* for a specific automotive component: a suspension arm (hereafter SA). The method adopted is a combination of a ***Life Cycle Assessment (LCA)*** and a ***Life Cycle Costing (LCC)*** as a part of Life Cycle Sustainability Assessment (LCSA) analysis.

The purpose is to make evidence on which of the different materials and technologies combination (five alternatives) cause the most environmental impact and economic expenditure, considering the full product life cycle. For this purpose, the perimeter of the analysis includes all the phases upstream and downstream of the MM production stage, performing in this way what is so called “cradle to grave” approach analysis.

Overall, the main goals of the project are:

- verify applicability of LCA and LCC as a supporting tool to “identify the main sustainability hotspots in the product life cycle - especially regarding its technology function during its operation on the vehicle - therefore guide strategy development” and provide elements for production decisions for SA production;
- develop data collection on environmental and economic impact of the different production technologies regarding the manufacturing of a SA;
- simulate different alternatives scenario with various materials and technology application to the same component;
- create a model for the environmental assessment of a specific material and technology;
- provide guidance on different product design proposals based on environmental and economic impact point of view.

7.4.1 GOAL AND SCOPE

The overall scope of the study is to quantify the environmental and economic impacts of the entire suspension arm life cycle, comparing with different innovative alternative design, differentiating with

alternative materials (primary materials, secondary materials and polymer) the whole SA and its sub-components (shells, rings, tubes).
The main driver taken into account for improvement is the *lightweighting* effect.

The present analysis can be used to supply sustainability information to improve product performances in terms of:

- life cycle perspective to assess a balance among environment and economic point of view, two different manufacturing technologies for the production of a specific component to apply at macro-level;
- find insight in the specific context of manufacturing plant and in the implementation of secondary and or virgin material (aluminium);
- quantifying energy and resource intensive processes and minimizing their impact.

In order to assess the environmental and economic impact of the innovative production technology to be implemented for the manufacturing of a SA, a comparative LCA and eLCC between the 5 different design solutions has been accomplished. The main technical difference data of the two design solutions are reported in Table 36. The consequences of production technology variation are: i) the change of the production technology and ii) the sub-components' weight with no geometry variation.

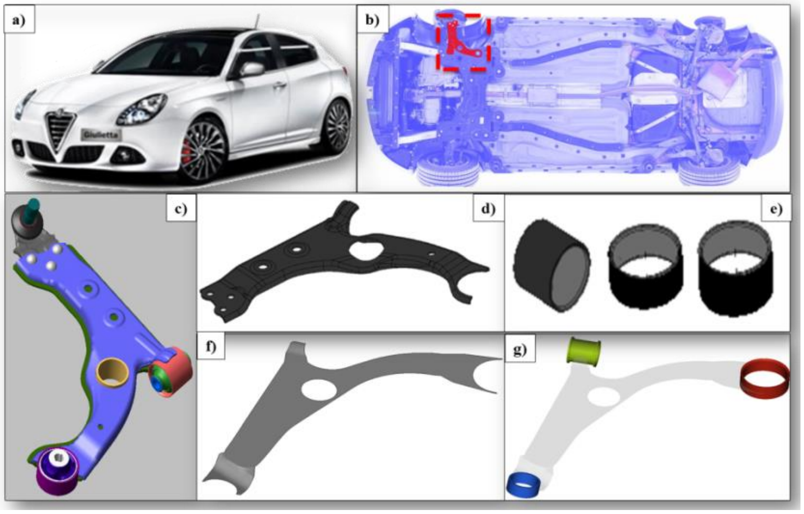
Table 36 - Technical data of crossmember design solutions.

Features	Standard Design	Innovative design first solution [A]	Innovative design second solution [B]	Innovative design third solution [C]	Innovative design fourth solution [D]	Variation
Weight (kg)	2.23	1.277	1.527	1.277	1.295	Weight reduction -43% ref. A and ref. C; -30% ref. B; -42%D
Parts	a) 2 shells (steel)	a) 1 reinforcement (primary aluminum)	a) 1 reinforcement (steel)	a) 1 reinforcement (secondary aluminum)	a) 1 reinforcement (steel)	a) component substitution (*shells* with *reinforcement*) and materials
	b) 3 rings (steel)	b) 3 rings (primary aluminum)	b) 3 rings (steel)	b) 3 rings (secondary aluminum)	b) 3 rings (steel)	b) materials (except for B)
	c) Tubes cutting	c) Tubes cutting (composite polymer PA66+60% GF)	c) Tubes cutting (composite polymer PA66+60% GF)	c) Tubes cutting (composite polymer PA66+60% GF)	c) Tubes cutting (composite polymer PA66+40% CF)	c) addition of *tubes cutting component*
Production Technology	1. MAG Welding (shells with rings)	1. MIG Welding (reinforc. with rings)	1. MAG Welding (reinforc. with rings)	1. MIG Welding (reinforc. with rings)	1. MAG Welding (reinforc. with rings)	Manufacturing process for component and technology variation
	2. Painting (pretreatment + cataphoresis)	2. Co-molding (welded parts with composite polymer)	2. Co-molding (welded parts with composite polymer)	2. Co-molding (welded parts with composite polymer)	2. Co-molding (welded parts with composite polymer)	Manufacturing process for component and technology variation

7.4.2 COMPONENT DESCRIPTION

The suspension arm takes part in the suspension system of the vehicle (Figure 58). The main functions of the component are to absorb the road shock and to maintain tire-to-road contact. Nevertheless, such a component must also ensure strict technical performances, mainly in terms of safety in case of collisions. The alternative solutions are proposed as a lighter alternative design that performs the same functional requirement of the standard design solution. In particular, all the alternatives are metal/plastic hybrid solutions where the plastic composite material is co-molded with the metal reinforcement.

Figure 58 – a) Reference vehicle, b) suspension arm location within the vehicle c) suspension arm design, d) upper shell, 3) rings, f) lower shell, g) bushings.



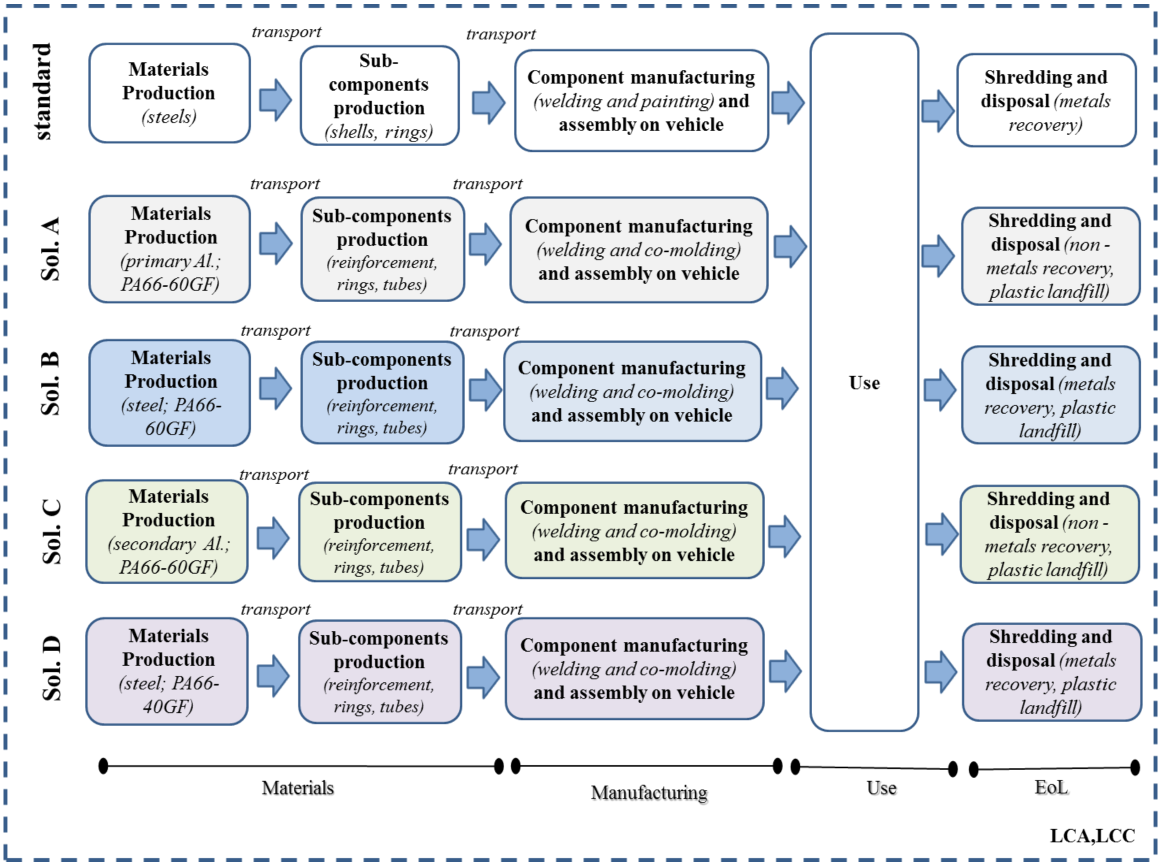
7.4.3 SYSTEM BOUNDARIES AND FUNCTIONAL UNIT

In this paragraph, the product system and the system boundaries are described. Regarding the system boundary, LCA and LCC are conducted by defining product systems as models that describe the key elements of physical systems. The system boundary defines the unit processes to be included in the system. Ideally, the product system is modelled in such a manner that inputs and outputs at its boundary are elementary flows. The choice of the elements of the physical system to be modelled depends on the goal and scope definition of the study. The different SA design options are analyzed as integrated within the suspension system through all its life cycle, according to a “cradle to gate” approach, splitting it in the following macro-phases: materials, manufacturing, use, end of life and transport of each phase in between. For the present case study are considered the life cycle phase grouped according to:

- materials which includes raw materials extraction and their processing;
- manufacturing accounts for all the process involved within MM perimeter to produce the muffler;
- transport assess the impact attributed to all the shipments for the life cycle phases in between;
- use is based on component operation within the reference vehicle selected for a specific life time mileage;
- end of life: consists of all the process involved to recover/disposal of the materials (after vehicle dismiss) according to their typology.

Following Figure 59 characterizes SA life cycle phases for both scenarios. The five design solution differs for the: material, manufacturing and transport. The Functional Unit (FU) of the present analysis is one *suspension arm* integrated within suspension system, supporting and housing all the instrumentation for vehicle use, to be mounted on a 4 Turbo 105 HP Alfa Romeo Giulietta, gasoline car for 150,000 km on 10 years.

Figure 59 – Suspension arm case study system boundary.



7.4.4 LCA ANALYSIS

Here is presented the LCA methodology application on SA design solutions.

7.4.4.1 LIFE CYCLE INVENTORY (LCI)

In this sub-paragraph data collection to quantify relevant inputs and outputs of the phases which compose product life cycle is described. Where possible process parameters (materials and energy flows) were obtained by direct measurements on industrial processes and/or estimation; in the others cases assumptions from GaBi 6.115 processes database have been used. In Table 37, Table 38, Table 39,

Table 40 and Table 41 a description of modalities used to collect data is reported. The materials compositions and production are grouped with the reference of Gabi datasets and data quality. The Use stage covers the operation of the SA integrated within the exhaust system of the vehicle selected. It reflects the fuel consumption linked to the mass during the life time of a vehicle. To calculate impact imputable to the component operation over the vehicle life time [150,000 km], it was used an analytical model proposed by (Koffler and Rohde-Brandeburger 2010) considering the parameters in Table 42. In the end of life phase, the suspension arm is usually managed at the shredder that is after the vehicle is treated by dismantler and pressed. Therefore, the car wreck, which includes inside the suspension arm component, is then shredded and material flows are sorted and addressed to the better end of life way according to the material typology. In the LCA study, the end of life has been evaluated considering:

- process burdens due to the ELV shredding and referred to the F.U. by weight;
- recycling credits due to the avoided raw material production, which is bauxite for aluminium and coke for steel. Besides, an economical allocation, which takes into account ratio between the scrap class and the LME primary metal price, has been used to estimate the recycling quota;
- waste management burdens due to the landfill disposal. As a matter of fact, the plastic part of the component represents the so called Automotive Shredder Residue (ASR), which is the shredding residue that, by now in Italy, is landfilled.

Table 37 - LCI suspension arm standard design solution [steel].

	Standard Design		
Life cycle phase	**Specification**	**Quantity** *(per FU)*	**Process** *(GaBi; ecoinvent)*
Materials	Stainless steel [Fe510D] - for shells production	1.88 kg	Steel hot rolled coil
	Stainless steel [S700MC] - for rings production	4.5x10-1 kg	Steel UO pipe
	Carbon Dioxide [CO2] (gaseous) - auxiliary for welding production process	1.45 x10-2 kg	Carbon dioxide
	Argon [Ar] (gaseous) - auxiliary for welding	6.9 x 10-2 kg	Argon
	Ethanol - auxiliary for welding production process	4x10-5 kg	Ethanol (96%)
	Copper tube (metal) - auxiliary for welding	5.1x10-5	Copper tube
	Polypropylene [PP] film (plastic) - auxiliary for welding production process	1.1 x 10-5 kg	Polypropylene film (PP) (Plastics Europe)
	Corrugated board boxes - auxiliary for welding	6.3x10-4 kg	Corrugated board boxes (ELCD/FEFCO)
	Steel wire rod (metals) - auxiliary for welding	5.1x10-2 kg	Steel wire rod (worldsteel)
	Water (deionized) - auxiliary for painting	5.85 kg	Water (deionized)
	Tap Water - auxiliary for painting	17.6 kg	Tap water
	Wastewater treatments process - auxiliary for water disposal after painting process	23.4 kg	Municipal waste water treatment (sludge incineration)
	Methane [CH4] (gaseous) - auxiliary for painting	1.22x10-1 kg	Methane
	Coating electrodeposition mix - auxiliary for painting	4.1x10-3 kg	Coating electrodeposition mix
	Chemicals (degreasing, phosphating) - auxiliary for painting	2.03x10-3 kg	Pretreatment chemicals (degreasing, phosphating)
Manuf.	Welding suspension arm	4.75 kWh	Electricity grid mix (IT)
	Painting suspension arm	7.2 kWh	Electricity grid mix (IT)
Logistic	Total segments distance travelled (2 sub-components suppliers)	890 km	Truck-trailer, Euro 5, 28 - 34t gross weight / 22t payload capacity
EoL	Shredding (within drained vehicle) → Materials separation → Metals recovery	(only materials)	Car shredder (Gabi); Steel - scrap credit (open loop); Coke mix

Table 38 - LCI suspension arm first innovative design solution [A] [primary aluminium + polymer].

	Innovative design first solution [A]		
Life cycle phase	**Specification**	**Quantity** *(per FU)*	**Process** *(GaBi; ecoinvent)*
Materials	Primary aluminum - reinforcement production	2.06x10-1	Aluminium foil
	Primary aluminum - for rings production	8.24x10-2 kg	Aluminium profile; Aluminium extrusion profile
	Polyamide 66 [PA66] - compounding for co-molding	4.45x10-1 kg	Polyamide 6.6 Granulate (PA66)
	Glass Fibers [GF]	6.67x10-1 kg	Glass fibres
	Argon [Ar] (gaseous) - auxiliary for welding production process	9.27 x 10-2 kg	Argon
	Ethanol - auxiliary for welding production process	4x10-5 kg	Ethanol (96%)
	Copper tube (metal) - auxiliary for welding production process	4x10-5	Copper tube
	Polypropylene [PP] film (plastic) - auxiliary for welding production process	7 x 10-6 kg	Polypropylene film (PP) (Plastics Europe)
	Corrugated board boxes - auxiliary for welding production process	4.02x10-4 kg	Corrugated board boxes (ELCD/FEFCO)
	Aluminium alloy AlMg3 - auxiliary for welding production process	1.8x10-2 kg	Aluminium alloy, AlMg3
	Lubricating oil - auxiliary for co-molding production process	2.87x10-4 kg	Lubricating oil
Manuf.	Welding suspension arm	3.27x10-1 kWh	Electricity grid mix (IT)
	co-molding suspension arm	1.3 kWh	Electricity grid mix (IT)
Logistic	Total segments distance travelled (2 sub-components suppliers and 1 material supplier (compound))	1,400 km	Truck-trailer, Euro 5, 28 - 34t gross weight / 22t payload capacity
EoL	Shredding (within drained vehicle) → Materials separation → Metals recovery	(only materials)	Car shredder ; Aluminium - scrap credit (open loop); Aluminium hydroxide mix (bauxite mix), Plastic landfill

Table 39 - LCI suspension arm second innovative design solution [B] [steel + polymer].

	Innovative design second solution [B]		
Life cycle phase	**Specification**	**Quantity** *(per FU)*	**Process** *(GaBi; ecoinvent)*
Materials	Stainless steel [Fe510D] - for shells production	0.36 kg	Steel hot rolled coil
	Stainless steel [S700MC] - for rings production	4.5x10-1 kg	Steel UO pipe
	Polyamide 66 [PA66] - compounding for co-molding	4.45x10-1 kg	Polyamide 6.6 Granulate (PA66)
	Glass Fibers [GF]	6.67x10-1 kg	Glass fibres
	Carbon Dioxide [CO2] (gaseous) - auxiliary for welding	1.16 x10-2 kg	Carbon dioxide
	Argon [Ar] (gaseous) - auxiliary for welding	7.8 x 10-2 kg	Argon
	Ethanol - auxiliary for welding production process	4x10-5 kg	Ethanol (96%)
	Copper tube (metal) - auxiliary for welding production process	4x10-5 kg	Copper tube
	Polypropylene [PP] film (plastic) - auxiliary for welding	4x 10-6 kg	Polypropylene film (PP) (Plastics Europe)
	Corrugated board boxes - auxiliary for welding	2.23x10-4 kg	Corrugated board boxes (ELCD/FEFCO)
	Steel wire rod (metals) - auxiliary for welding	1.8x10-2 kg	Steel wire rod (worldsteel)
	Lubricating oil - auxiliary for co-molding	2.87x10-4 kg	Lubricating oil
Manuf.	Welding suspension arm	3.27x10-1 kWh	Electricity grid mix (IT)
	Co-molding suspension arm	1.3 kWh	Electricity grid mix (IT)
Logistic	Total segments distance travelled (2 sub-components suppliers and 1 material supplier (compound))	1,400 km	Truck-trailer, Euro 5, 28 - 34t gross weight / 22t payload capacity
EoL	Shredding (within drained vehicle) -> Materials separation -> Metals recovery	(only materials)	Car shredder (Gabi); Steel - scrap credit (open loop); Coke mix; Plastic landfill

Table 40 - LCI suspension arm second innovative design solution [C] [secondary aluminium + polymer].

	Innovative design third solution [C]		
Life cycle phase	**Specification**	**Quantity** *(per FU)*	**Process** *(GaBi; ecoinvent)*
Materials	Secondary aluminum - reinforcement production	2.06x10-1	Aluminium recycling incl. scrap preparation
	Secondary aluminum - for rings production	8.24x10-2 kg	Aluminium recycling incl. scrap preparation ; Aluminium extrusion profile
	Polyamide 66 [PA66] - compounding for co-molding	4.45x10-1 kg	Polyamide 6.6 Granulate (PA66)
	Glass Fibers [GF]	6.67x10-1 kg	Glass fibres
	Argon [Ar] (gaseous) - auxiliary for welding production process	9.27 x 10-2 kg	Argon
	Ethanol - auxiliary for welding production process	4x10-5 kg	Ethanol (96%)
	Copper tube (metal) - auxiliary for welding production process	4x10-5	Copper tube
	Polypropylene [PP] film (plastic) - auxiliary for welding production process	7x10-6 kg	Polypropylene film (PP) (Plastics Europe)
	Corrugated board boxes - auxiliary for welding production process	4.02x10-4 kg	Corrugated board boxes (ELCD/FEFCO)
	Aluminium alloy AlMg3 - auxiliary for welding	1.8x10-2 kg	Aluminium alloy, AlMg3
	Lubricating oil - auxiliary for co-molding production process	2.87x10-4 kg	Lubricating oil
Manuf.	Welding suspension arm	3.27x10-1 kWh	Electricity grid mix (IT)
	co-molding suspension arm	1.3 kWh	Electricity grid mix (IT)
Logistic	Total segments distance travelled (2 sub-components suppliers and 1 material supplier (compound))	1,400 km	Truck-trailer, Euro 5, 28 - 34t gross weight / 22t payload capacity
EoL	Shredding (within drained vehicle) → Materials separation → Metals recovery	(only materials)	Car shredder; Aluminium - scrap credit (open loop); Aluminium hydroxide mix (bauxite mix), Plastic landfill

Table 41 - LCI suspension arm second innovative design solution [D] [steel + innovative polymer].

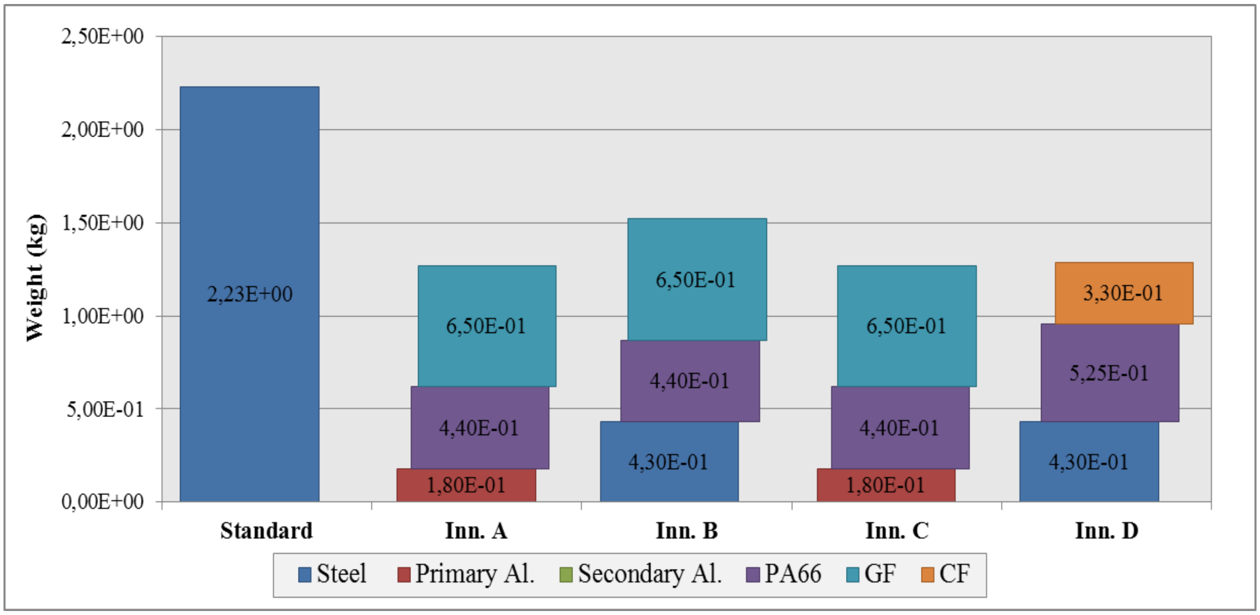
	Innovative design fourth solution [D]		
Life cycle phase	**Specification**	**Quantity** *(per FU)*	**Process** *(GaBi; ecoinvent)*
Materials	Stainless steel [Fe510D] - for shells production	0.36 kg	Steel hot rolled coil
	Stainless steel [S700MC] - for rings production	4.5x10-1 kg	Steel UO pipe
	Polyamide 66 [PA66] - compounding for co-molding	5.15x10-1 kg	Polyamide 6.6 Granulate (PA66)
	Carbon Fibers [CF]	3.35x10-1 kg	Carbon Fibre (CF; from PAN)
	Argon [Ar] (gaseous) - auxiliary for welding production process	9.27 x 10-2 kg	Argon
	Carbon Dioxide [CO2] (gaseous) - auxiliary for welding production process	1.64 x10-2 kg	Carbon dioxide
	Ethanol - auxiliary for welding production process	4x10-5 kg	Ethanol (96%)
	Copper tube (metal) - auxiliary for welding production process	4x10-5	Copper tube
	Polypropylene [PP] film (plastic) - auxiliary for welding production process	4x10-6 kg	Polypropylene film (PP) (Plastics Europe)
	Corrugated board boxes - auxiliary for welding production process	2.23x10-4 kg	Corrugated board boxes (ELCD/FEFCO)
	Steel wire rod - auxiliary for welding production process	1.8x10-2 kg	Steel wire rod
	Lubricating oil - auxiliary for co-molding production process	2.87x10-4 kg	Lubricating oil
Manuf.	Welding suspension arm	3.27x10-1 kWh	Electricity grid mix (IT)
	co-molding suspension arm	1.3 kWh	Electricity grid mix (IT)
Logistic	Total segments distance travelled (2 sub-components suppliers and 1 material supplier (compound))	1,400 km	Truck-trailer, Euro 5, 28 - 34t gross weight / 22t payload capacity
EoL	Shredding (within drained vehicle) → Materials separation → Metals recovery	(only materials)	Car shredder ; Steel - scrap credit (open loop); Coke mix; Plastic landfill

Table 42 - LCI Use phase, vehicle technical data and model parameter for suspension arm.

Technical data referring to car model		
Vehicle technical charateristic	Model	Alfa Romeo Giulietta 1.4 Turbo gasoline 105 CV (77.2 kW)
	Mass	1280
	Emission stage	EURO 5
	Motorway per-km CO_2 emission [g/km]	149
	Mixed consumption [l/100km]	6.4
Operation	Vehicle life time [km] - dm	150,000
Analytic model [NEDC]	Mass induced fuel consumption [l/100km*100kg] - FRV_PMR [Gasoline] - fm	0.15
Mass [m]	Vehicle equipped with standard suspension arm[kg]	2.23
	Vehicle equipped with first innovative suspension arm [A] [kg]	1.277
	Vehicle equipped with second innovative suspension arm [B] [kg]	1.527
	Vehicle equipped with fourth innovative suspension arm [D] [kg]	1.295
Fueldensity	Gasoline [kg/dm³]	0.74
Specific consumption [kg/kg fuel]	CO_2 emissions generated during the consumption of 1 kg of fuel [kg CO_2/Kg fuel] – f_{CO2}	3.12
	SO_2 emissions generated during the consumption of 1 kg of fuel [kg SO_2/Kg fuel] - f_{SO2}	0.00015

Figure 60presents the materials breakdown within the various SA scenarios according to their composition and weight contribution. The four innovative design proposal present a different structure, where the steel is completely substituted with aluminium and plastic composite (solution A and C) and or part of the sub-components are produced with steel and plastic composite (B and D). Considering plastic compound, two possible materials are employed: one proposal is PA66 reinforced with GF, which is used for the production of A, B, and C innovative solution. Alternatively, in the innovative D proposal the PA66 is reinforced with CF. The heaviest component is the standard solution, followed by B: the two components design differs from the plastic matrix which for the standard is constituted by PA6, and whereas for the innovative is PP. The only variation regarding A and C scenario is due to employment of virgin aluminum (A proposal) and secondary aluminium (C proposal). The lightest components are A and C.

Figure 60 – Suspension arm design solutions materials breakdown.

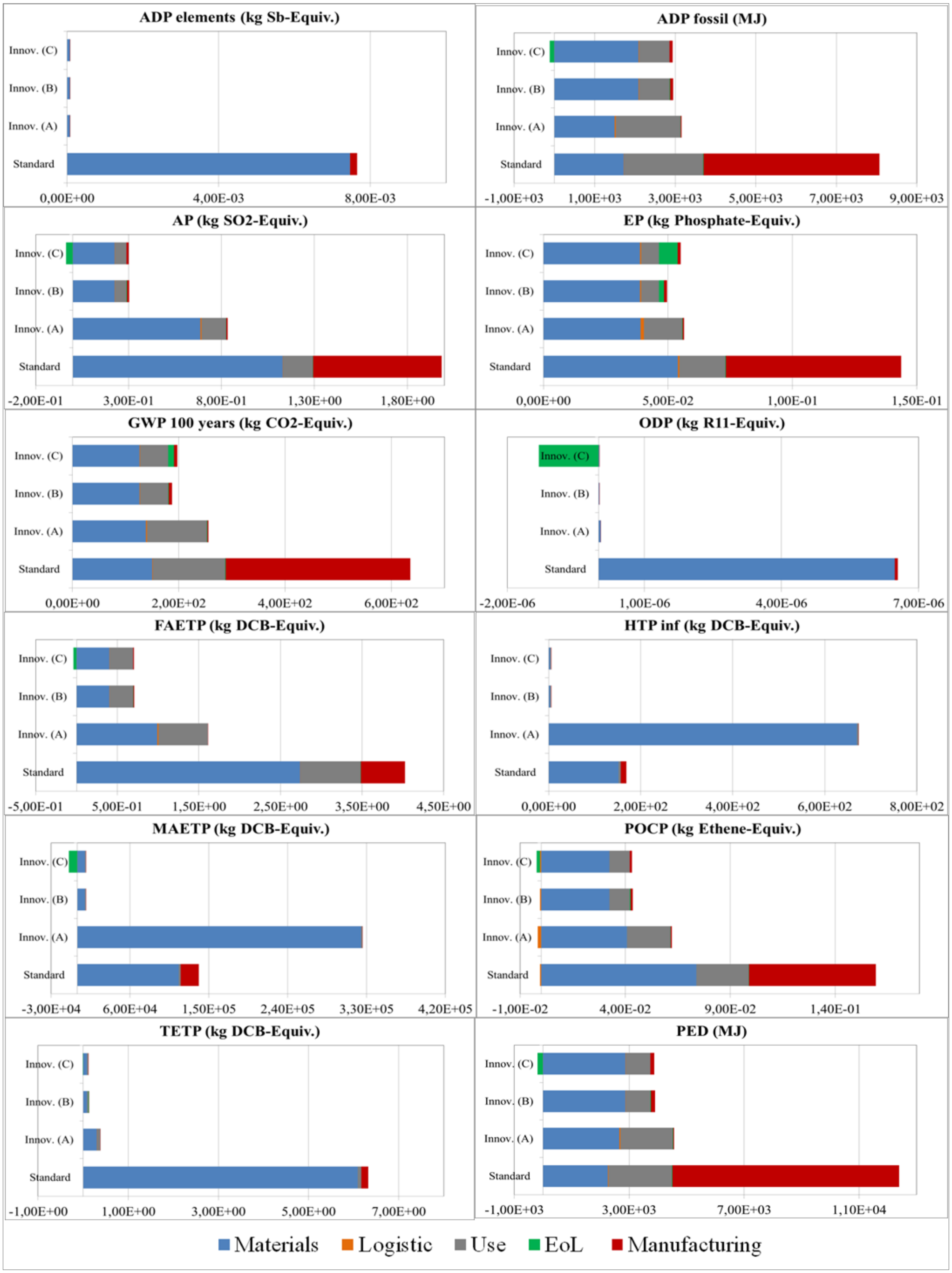


In the modeling of auxiliary module‘s life cycle, the packaging consumption have been excluded since materials are always recovered for the same purposes.

7.4.4.2 LCA LIFE CYCLE IMPACT ASSESSMENT (LCIA)

In this section life cycle environmental impact has been calculated on the basis of data gathered during the inventory; it has been done by applying *Classification* and *Characterisation* to LCI data according to ISO 14040 standard guidelines. The results of Life Cycle Impact Assessment are reported below; this has been obtained according to *CML 2001 Apr. 2016*regulations, the *Primary Energy Demand (PED)* category from renewable and non-renewable resources (gross cal. value) has been considered. Results are presented in Figure 108 in a form to show, for each class of environmental impact, the contribution of each life cycle stage, on the total impact, for the two design solutions, whereas the total impact percentages delta [Δ%] for each impact indicator are reported in Figure 61.

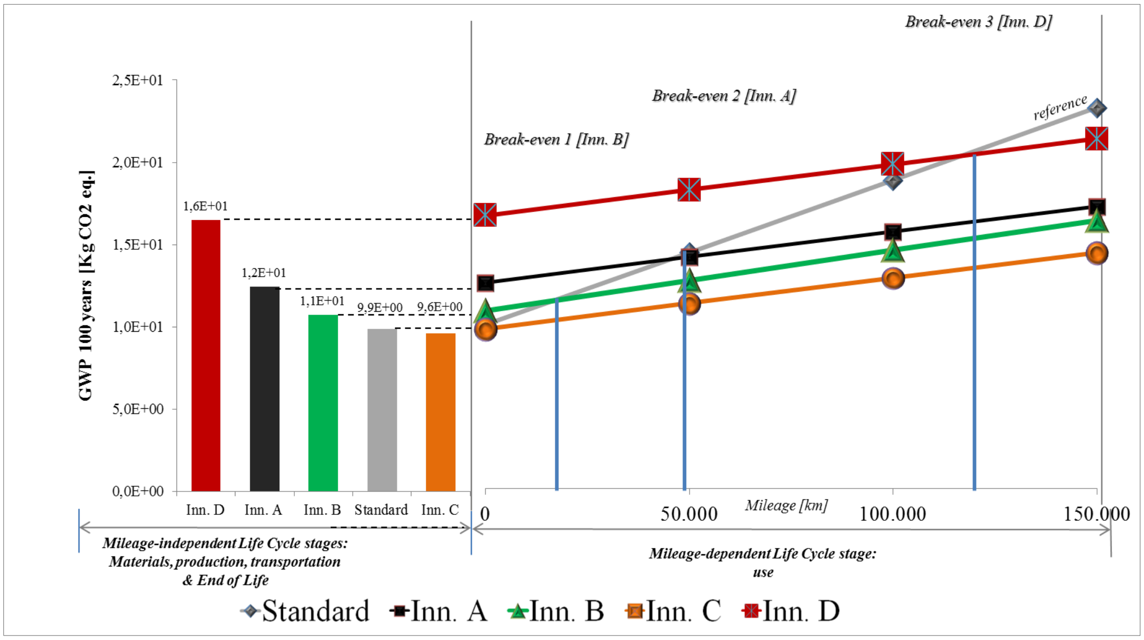
Figure 61 – LCIA Results for suspension arm.



GHG EMISSIONS BREAK-EVEN

In Figure 62 is reported the GHG emissions of CO_2 over the life cycle contribution of the standard SA and the four alternative scenarios. The total amount is separated according to static attribution, accounted for the upstream and downstream activities, with reference of the component operational use. From the bar chart we can observe that the highest emissions are generate from *D* solution (steel + CF composite), followed by *A* (primary al + GF-composite) wherease the lowest are generated from *C* alternative design (secondary aluminium and plastic composite). From the graphs can be clearly distinguished three break-even points with reference on the standard (grey line). The first occurs with the design *B* whose weight is 1.57 kg at roughly 20,000 km. Whereas the second with *A* solution (1.277 kg) at about 50,000 km. The last point sign the counterbalance with *D*design whose weight is (1.29 kg). Indeed, the lowest emissions are generated by the *C*component, which is the lightest (1.277 kg) one.

Figure 62 – GHG emissions break-even suspension arm project.



7.4.4.3 LCA INTERPRETATION

In this final section, the results obtained and previously shown for each process separately are now compared and interpreted. Comparing all the solutions, it is evident that use phase is the main contribution to the GWP impact and so weight reduction is surely one of the most important actions to improve the environmental footprint of the product. The advantages of lightweighting are double, as a matter of fact, it is possible to cut the car fuel consumption and, as a consequence, also the air emissions.

In particular, carbon dioxide is the emission that affects mainly the GWP impact. Taking into account also the other contributions to the GWP, the material eco-profiles show an important effect. Such an effect is evident considering solutions with carbon fibres. Actually, the carbon fibres manufacturing, that is the carbonization, is well known to be a very energy-consuming process. Other lifecycle phases, such as manufacturing, transportation or end of life, do not affect significantly the GWP impact.The same considerations are valid for the material eco-profiles and mainly for the carbon fibres. In fact, the effect of the carbonization process is evident since it is very energy consuming. Another material, which shows an important environmental burden, is the primary aluminium. The use of secondary aluminium allows to cut down such a contribute. The main difference referring to the GWP impact is the steel production since it has a great effect in terms of air emissions, but not in terms of energy consumption. Also for this impact, manufacturing, transportation and end of life are not relevant taking into account the whole life cycle of the product.

Comparing the solutions, it is evident how the primary aluminium is worsening mainly because of the MAETP impact. The innovative solutions with glass fibres show a significant contribution for the ADP elements impacts, which is indeed due to the glass fibres. Instead, the solution with carbon fibres is worse for those impacts linked to the energy consumption since the carbon fibres manufacturing process is very energy consuming. Logistic, manufacturing and EoL present a minor contribution with the exception of component where MAG welding occurs. In fact to produce steel high impact is generated from the production process and also for the MAG welding process due to the employment of Al-Mg wire.

Environmental impacts depend mainly on raw materials eco-profiles and use phase so the more significant improvement points consist on a choice of raw materials o weight reduction taking also into account the material performances, e.g. aluminium allows a good weight reduction, but the use of primary resource leads to have a worst solution from the environmental impacts point of view. Even if steel is not so advantageous because of its high density, use of steel plastic hybrid can be reasonably considered a good solution compare to standard production due to the technical feasibility, the environmental performances and weight reduction. From an environmental point of view the aluminium plastic hybrid is the solution more and more environmentally friendly increasing the secondary aluminium percentage. The carbon fibres solution would ensure good performances considering all the environmental impacts, but, actually, it does not provide so many advantages focusing the attention on the two main environmental impacts (GWP and PED). All the plastic composite solutions, evaluated in the study, could present decrease of different environmental impacts thinking to a recycling way for plastic and glass/carbon fibres. In the study, such a way was not considered since dismantlers for recycling do not disassemble the component. From the GHG emissions break-even the following conclusion could be drawn: the lowest emissions are attributed to the lightest material using secondary aluminium profile, since in the equal weight scenario (A) a higher numbers of CO2 emissions are generated upstream for the production of a virgin aluminum.

7.4.5 ENVIRONMENTAL LIFE CYCLE COSTING

The following section describes the eLCC analysis of the SA case study.

7.4.5.1 LIFE CYCLE INVENTORY [LCI]

The unit costs are given in Table 43 and according to what described in CHAPTER 5 (paragraph 5.1.2 *LCC methodology in Magneti Marelli*).

Regarding the environmental eLCC the total cost is attributed from conventional LCC with the addition of the cost derived by the CO2 emissions generated during component LC (accounting materials, manufacturing, logistic, EoL and use over 150,000 kilometers of use) and their damage cost [€/kg emissions]. The Clean Vehicles Directive 2009/33 /EC. provide valuations of specific environmental damage cost. CO2 emissions were already calculated from LCA analysis.

Table 43 – LCC inventory suspension arm project standard and innovative design solutions.

Life cycle phase	Flow (*per FU)	Unit cost	Source
Manufacturing	Electricity	0.12 €/kWh (average European)	*Eurostat, 2018*
	Electricity (injection molding)	0.575 kWh	*Primary data*
Use	Gasoline	1.46 €/litre (avg European price)	*IEA, 2018*
	CO_2 emissions cost	4.00 x 10^{-5} €/gCO_2	*European Commission*
	CO2 emissions	Standard [W] 13.27 KgCO_2	*Primary data*
		Standard [B] 13.74 KgCO_2	
EoL	Electricity	0.12 €/kWh (average European)	*Eurostat, 2018*
	Steel recovery	0.19 €/kg	*Primary data*
	Non metal recovery	0.38 €/kg	
	Metals recovery	0.19 €/kg	
	Plastic disposal [Worst case]	0.1 €/kg	

7.4.5.2 eLCC IMPACT ASSESSMENT [LCIA]

In Table 44 are presented the total cost attributable to the brake pedal from different perspective, internalizing the cost attributable to user during vehicle use and EoL management to recover and/or disposal the relative materials. Economic assessment results are described according to the following cost categories: manufacturing, transports, use and end-of-life. 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 calculation of each contribution has been accomplished as reported below:

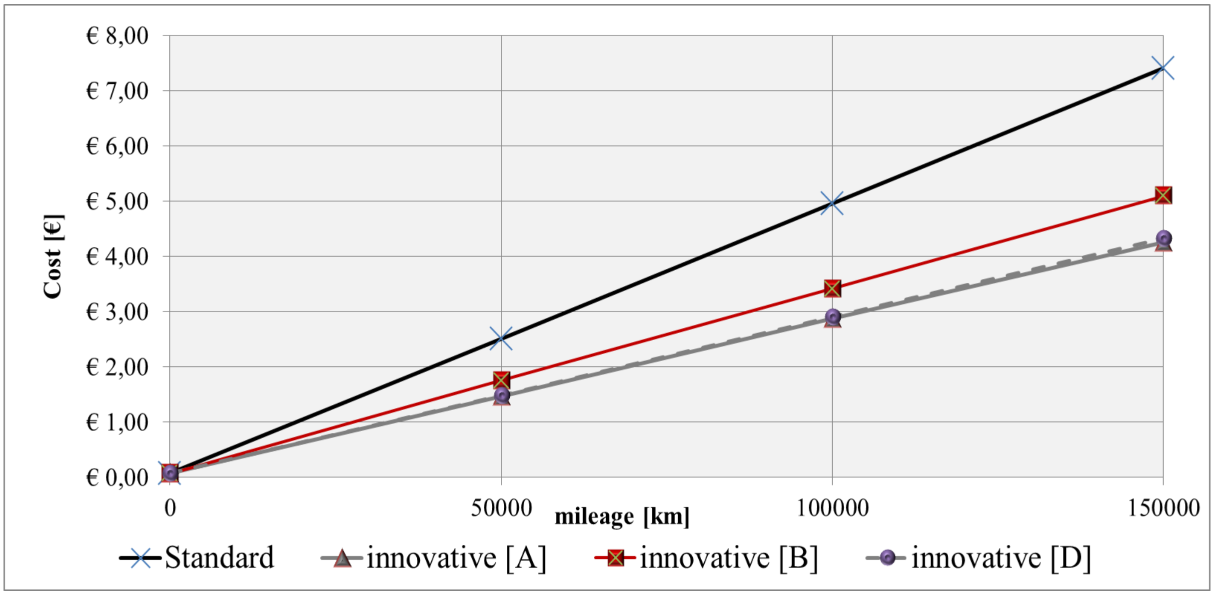
- for transport: the incidence of the cost per km multiplied by the total distance traveled and divided by truck payload capacity;
- for manufacturing: the cost attributable to each production item considering the contribution of machine costs;
- for use: the total fuel consumption during vehicle life-time mileage of 150,000 km attributable to each component, multiplied by the average European cost of gasoline fuel;
- for EoL: the cost attributable to the disposal and/or recovery of each material flow within the dismantle line of vehicle.

Table 44 - eLCC results suspension arm project.

Reference	**Flow**	**Standard**	**Innov. [A]**	**Innov.[B]**	**Innov. [C]**	**Innov.[D]**
Transport	Distance travelled	€ 0,073	€ 0,066	€ 0,078	€ 0,066	€ 0,07
Manufacturing	Production	€ 1,43	€ 0,19	€ 0,19	€ 0,19	€ 0,19
Total cost (MM perspective)		***€ 1,51***	***€ 0,26***	***€ 0,27***	***€ 0,26***	***€ 0,26***
Use	Fuel (150.000 km)	€ 7,4	€ 4,2	€ 5,02	€ 4,2	€ 4,25
	Externalities	€ 0,0009	€ 0,0007	€ 0,0006	€ 0,0006	€ 0,00
Total cost (user perspective)		***€ 7,33***	***€ 4,19***	***€ 5,02***	***€ 4,19***	***€ 4,25***
EoL	Materials separation	€ 0,093	€ 0,087	€ 0,066	€ 0,087	€ 0,06
	Materials recovery/dispose	-€ 0,443	-€ 0,383	-€ 0,08	-€ 0,38	-€ 0,10
Total life cycle cost		**€ 8,49**	**€ 4,15**	**€ 5,28**	**€ 4,15**	**€ 4,46**

Figure 63depicts the fuel consumption cost break-even analysis over the vehicle 150,000 km mileage of use. A sensitivity analysis reporting a comparison among the five scenarios (using discounting method) has been accomplished. From the line chart could be observed that the major spending are generated by the heaviest component. No differences are perceived from A and D alternative.

Figure 63 – Fuel cost break-even suspension arm project.



7.4.5.3 eLCC INTERPRETATION

From eLCC results could be distinguished the contribution of the total cost attributable to the five design alternative of SA activities. Indeed the most spending takes places during vehicle use, due to the fuel consumption and cost. Different consideration could be retrieved considering the different actors perspective. From MM perspective, the implementation of the innovative solution means a relevant production cost decrease in all the alternative cases. The MAG welding has indeed a high cost impact compared to MIG welding and co-molding. Further benefits are identified from user perspective, considering a cost decrease of fuel consumption, which increases proportioned to the mileage traveled. The less materials are processed in the EoL, the lower cost incomes are generated. The only advantage related to the employment of steel is related to the EoL phase due to the low energy expenditure for materials recovery. A part form that the steel solution represent not advantageous from economic point of view. To sum up, the implementation of the lighter innovative materials decrease the total cost over each LC dimensions, with more benefits related to the user perspective.Considering the total perspective, the highest price is attributed to standard € 8,49, followed by second scenario [B] accounting for € 5,28, secondary most contribution is represented by D solution € 4,46, and at the end the most convenient the A and C options with 4,14 €.

7.5 HALOGEN HEADLAMP REFLECTOR

This project focuses on the environmental impact assessment analysis between *two different materials* application for the production of specific automotive component: a halogen headlamp reflector (hereafter HHR). The method adopted is a combination of a ***Life Cycle Assessment (LCA)*** and a ***Life Cycle Costing (LCC)*** as a part of Life Cycle Sustainability Assessment (LCSA) analysis.

The purpose is to make evidence on which of the two materials cause the most environmental impact and economic expenditure, considering the full product life cycle. For this purpose, the perimeter of the analysis include all the phases upstream and downstream of the MM production stage, performing in this way what is so called "cradle to grave" approach analysis.
Overall, the main goals of the project are:

- verify applicability of LCA and LCC as a supporting tool to "identify the main sustainability hotspots in the product life cycle - especially regarding its technology function during its operation on the vehicle - therefore guide strategy development" and provide elements for production decisions for HHR production;
- develop data collection on environmental and economic impact of the different materials regarding the manufacturing of HHR;
- create a model for the environmental assessment of a specific materials;
- provide guidance on different product design proposals based on environmental and economic impact point of view.

7.5.1 GOAL AND SCOPE

The overall scope of the study is to quantify the environmental and economic impacts of the entire halogen headlamp reflector life cycle, comparing a reflector made of a *thermoset material (BMC),* which is also called as "standard design"; and a reflector made of a *thermoplastic material (PES)*, which is also called as "innovative design". The improvement lies in two main drivers: *lightweighting* and *banning of potential hazardous substances*. In fact the standard BMC material contains styrene, which is a critical substance according to IARC (International Agency for Research on Cancer) and REACH (Registration, Evaluation, Authorization and Restriction of Chemical substances); styrene is classified as «Reasonably anticipated to be a human carcinogen».

The present analysis can be used to supply sustainability information to improve product performances in terms of:

- life cycle perspective to assess a balance among environment and economic point of view, two different materials for the production of a specific component to apply at macro-level;
- find insight in the specific context of manufacturing plant;
- quantifying energy and resource intensive processes and minimizing their impact.

In order to assess the environmental and economic impact of the innovative production technology to be implemented for the manufacturing of a HHR, a comparative LCA and eLCC between the two different design solutions has been accomplished. The main technical difference data of the two design solutions are reported in Table 45. The consequences of production technology variation are: i) the change of the production technology and therefore the time cycle.

The analysis is focused on the reflector only, instead of the whole headlamp, since it would have been necessary to refer to generic secondary data (taken from literature or databases) for the materials and processes of the "buy" parts of the headlamp, with a poor added value to the study in question. This implied that, in the use phase, only the light weighting aspects have been taken into account, without considering the energy consumption due to the switch-on of the headlamp where the reflector is mounted on the vehicle. The reference MM plant is located in Czech Republic.

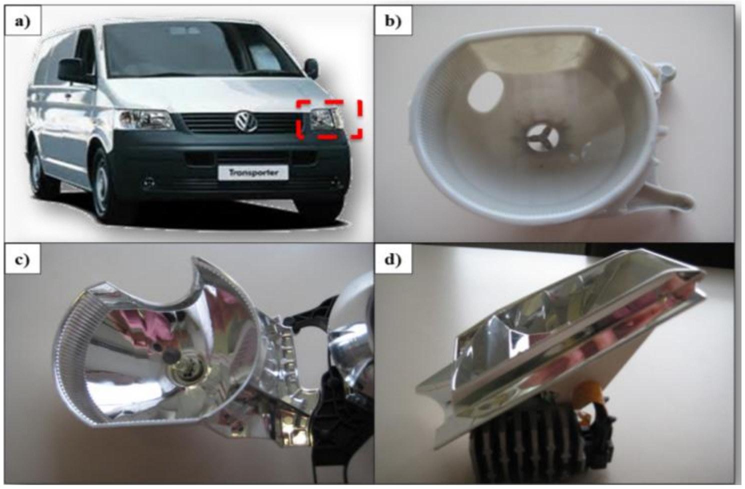
Table 45 - Technical data of halogen headlamp reflector design solutions.

Features	Standard	Innovative	Variation
Weight (kg)	0.380	0.250	34% weight reduction
Part/s	Reflector [thermoset - Bulk moulding compound (BMC)]	Reflector [thermoplastic - Polyether sulfone (PES)]	*Material*
Production technology	Storage → RIM → Burring cleaning → Lacquering → Metallization → Air blow cleaning	Injection Molding → Metallization → Air blowing	Production technology and time cycle

7.5.2 COMPONENT DESCRIPTION

The halogen headlamp reflector studied (Figure 64) is a component that takes part within the lighting system of a vehicle. The reflector delivers a diverse way of lighting, by means of reflected light with a parallel beam to accurately direct the light. The standard HHR is made of a thermoset material Bulk moulding compound (BMC) and a reflector made of a thermoplastic material Polyether sulfone (PES), which is also and identifies a heat-resistant, transparent, amber, non-crystalline engineering plastic.

Figure 64 – a) Reference vehicle, b) innovative headlamp [PES], c) standard headlamp [BMC], d) standard headlamp as produced.



7.5.3 SYSTEM BOUNDARIES AND FUNCTIONAL UNIT

In this paragraph, the product system and the system boundaries are described. Regarding the system boundary, LCA and LCC are conducted by defining product systems as models that describe the key elements of physical systems. The system boundary defines the unit processes to be included in the system. Ideally, the product system is modelled in such a manner that inputs and outputs at its boundary are elementary flows. The choice of the elements of the physical system to be modelled depends on the goal and scope definition of the study.The two HHR design options are analyzed as integrated within the lighting system of the vehicle through all its life cycle, according to a “cradle to gate” approach, splitting it in the following macro-phases: materials, manufacturing, use, end of life and transport of each phase in between.

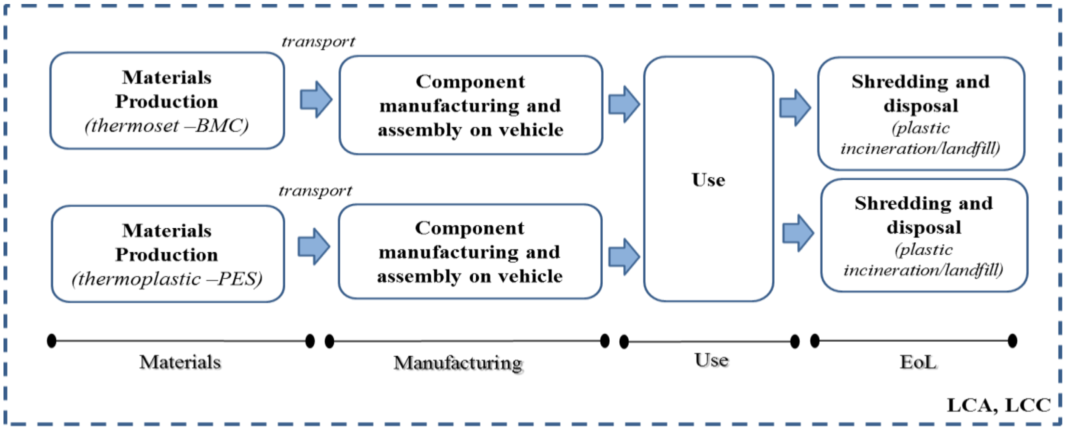
For the present case study are considered the life cycle phase grouped according to:

- materials which includes raw materials extraction and their processing;
- manufacturing accounts for all the process involved within MM perimeter to produce the muffler;
- transportassess the impact attributed to all the shipments for the life cycle phases in between;

- useis based on component operation within the reference vehicle selected for a specific life time mileage;
- end of life: consists of all the process involved to recover/disposal of the materials (after vehicle dismiss) according to their typology.

Following Figure 65characterizes HHR life cycle phases for both scenarios. The two design solutions differ for the material, manufacturing and transport. The Functional Unit (FU) of the present analysis is one *halogen headlamp reflector*T5 NUTZ integrated within lighting system, supporting and housing all the instrumentation for vehicle use, to be mounted a Volkswagen Minivan, gasoline car for 150,000 km on 10 years.

Figure 65 – Halogen headlamp reflector case study system boundaries.



7.5.4 LCA ANALYSIS

In the following paragraph are described the main step of the LCA analysis of the headlamp reflector.

7.5.4.1 LIFE CYCLE INVENTORY

In this sub-paragraph, data collection to quantify relevant inputs and outputs of the phases, which compose product life cycle, is described. Where possible process parameters (materials and energy flows) were obtained by direct measurements on industrial processes and/or estimation; in the others cases, assumptions from GaBi 6.115 processes database have been used. In Table 46 and Table 47 a description of modalities used to collect data is reported. The materials compositions and production are grouped with the reference of Gabi datasets and data quality. The Use stage covers the operation of the muffler integrated within the exhaust system of the vehicle selected. It reflects the fuel consumption linked to the mass during the life time of a vehicle. To calculate impact imputable to the component operation over the vehicle life time [150,000 km], it was used an analytical model proposed by (Koffler and Rohde-Brandeburger 2010) considering the parameters in Table 48. The EoL management options have been modeled according to the auxiliary module materials composition to separate plastic materials according to the following procedure: from metal recovery process → fluff treatment in press machine [to obtain compacted fluff]. Energy consumption calculation is based on the mass of the component to be treated according to the EoL options to recover/dispose certain material typology. Considering the nature of the component under examination, are also provided further information regarding process manufacturing, which for the standard are depicted in Figure 66 and , instead for the innovative in Figure 67.

Table 46 – LCA data collection standard headlamp reflector [BMC].

	Standard Design		
Life cycle phase	**Specification**	**Quantity** *(per FU)*	**Process** *(GaBi; ecoinvent)*
Materials	Reflector [thermoset - Bulk moulding compound (BMC)]	0.380 kg	Deionised water ; Process stem from natural gas 95%; Steam conversion; Electricity grid mix Polyester resin (unsatured); Benzoyl peroxide; Ethylene vinyl alcohol copolymer; Limestone flour (CaCO3); Glass fibers; Wastewater treatment (contains organic and inorganic load)
Logistic	Total segments travelled	784 km	Truck, Euro 5, 14 - 20t gross weight / 11,4t payload capacity
Manuf.	Storage	4x10-3 kWh	Electricity grid mix (CZ)
	RIM	3.08x10-1 kWh	Electricity grid mix (CZ)
		1.17x10-2 Nm3	Compressed air (EU-27)
		25 kg	Process water
		9.37x10-4 kg	Plastic packaging
		8.68x10-5 kg	Used oil
	Burring cleaning	3.55x10-2 kWh	Electricity grid mix (CZ)
		3.9x10-1 Nm3	Compressed air (EU-27)
	Lacquering	1.04 kWh	Electricity grid mix (CZ)
		8.12x10-1 Nm3	Compressed air (EU-27)
		7.11 kg	Process water
		6.3x10-2 kg	Natural gas (EU-27)
		4.44x10-3	Base coat solvent-based (red; metallic)
		4.38x1'-4 kg	Ethyl acetate
		1.51x10-3 kg	Plastic packaging
	Metallization	2.88x10-1 kWh	Electricity grid mix (CZ)
		7.47x10-2 Nm3	Compressed air (EU-27)
		30.8 kg	Process water

		2.94x10-4 kg	Section bar extrusion
		1.62x10-4 kg	Argon (gaseous)
		4.27x10-5 kg	Silicone
		3.88x10-7 kg	Used oil
		3.08x10-5 kg	Waste incineration of textile
		1.56x10-4 kg	Aluminum recycling incl. Scrap preparation
	Air blow cleaning	7.77x10-2 Nm3	Compressed air (EU-27)
EoL	1) Shredding (within drained vehicle) → Materials separation → plastic incineration	2.66x10-9 kWh	Electricity grid mix (CZ) EU-28: Plastic incineration;

Figure 66 –- Standard production process [BMC production] within MM manufacturing plant.

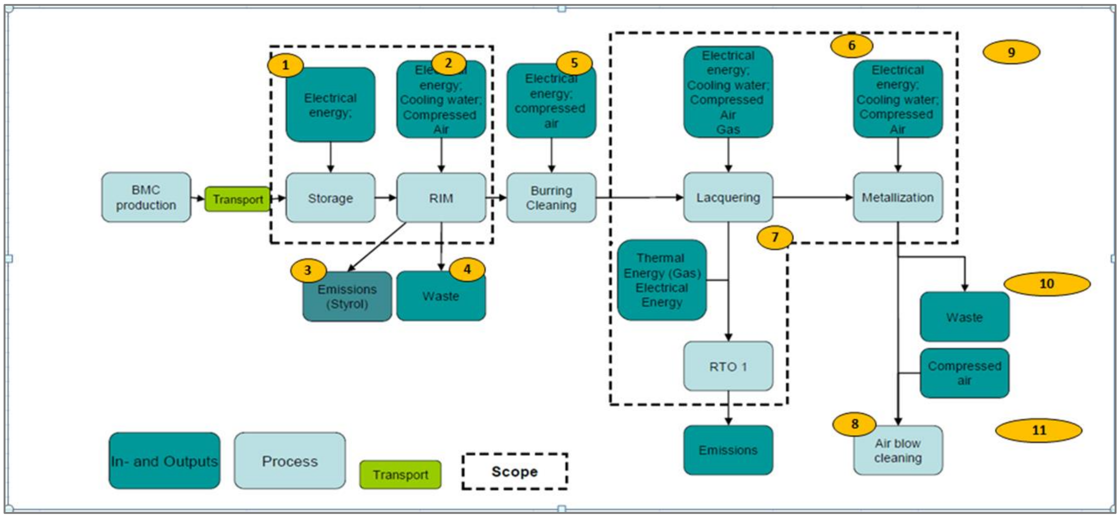


Table 47 – LCA data collection innovative halogen reflector [PES].

	Innovative Design		
Life cycle phase	**Specification**	**Quantity** *(per FU)*	**Process** *(GaBi; ecoinvent)*
Materials	Reflector [thermoplastic - Polyether sulfone (PES)]	0.250 kg	Dioxothiolane ; Benzene ; Potassium hydroxide (KOH); Methanol from natural gas; 4,4'-DCDPS (4,4'-Dichlorodiphenylsulfon); Deionised water; Nitrogen (Gaseous) ;Process stem from natural gas 95%; Steam conversion; Electricity grid mix; Wastewater treatment
Logistic	Total segments travelled	636 km	Truck, Euro 5, 7,5-12t gross weight / 5t payload capacity
Manuf.	Material drying	1.05x10-1 kWh	Electricity grid mix (CZ)

	Injection molding	2.83x10-1 kWh	Electricity grid mix (CZ)
		5.47x10-1 Nm3	Compressed air (EU-27)
		2.12x10-1 kg	Process water
		8.48x10-4 kg	Plastic packaging
		7.85x10-5 kg	Used oil
	Metallization	2.58x10-1 kWh	Electricity grid mix (CZ)
		6.67x10-2 Nm3	Compressed air (EU-27)
		27.5 kg	Process water
		2.63x10-4 kg	Section bar extrusion
		1.45x10-4 kg	Argon (gaseous)
		3.81x10-5 kg	Silicone
		2.75x10-7 kg	Used oil
		2.75x10-5 kg	Waste incineration of textile
		1.4x10-4 kg	Aluminum recycling incl. Scrap preparation
	Air blow cleaning	6.88x10-2 Nm3	Compressed air (EU-27)
EoL	1) Shredding (within drained vehicle) → Materials separation → plastic incineration	1.75x10-9 kWh	Electricity grid mix (CZ) EU-28: Plastic incineration;

Figure 67 - Innovative production process [PES production] within MM manufacturing plant.

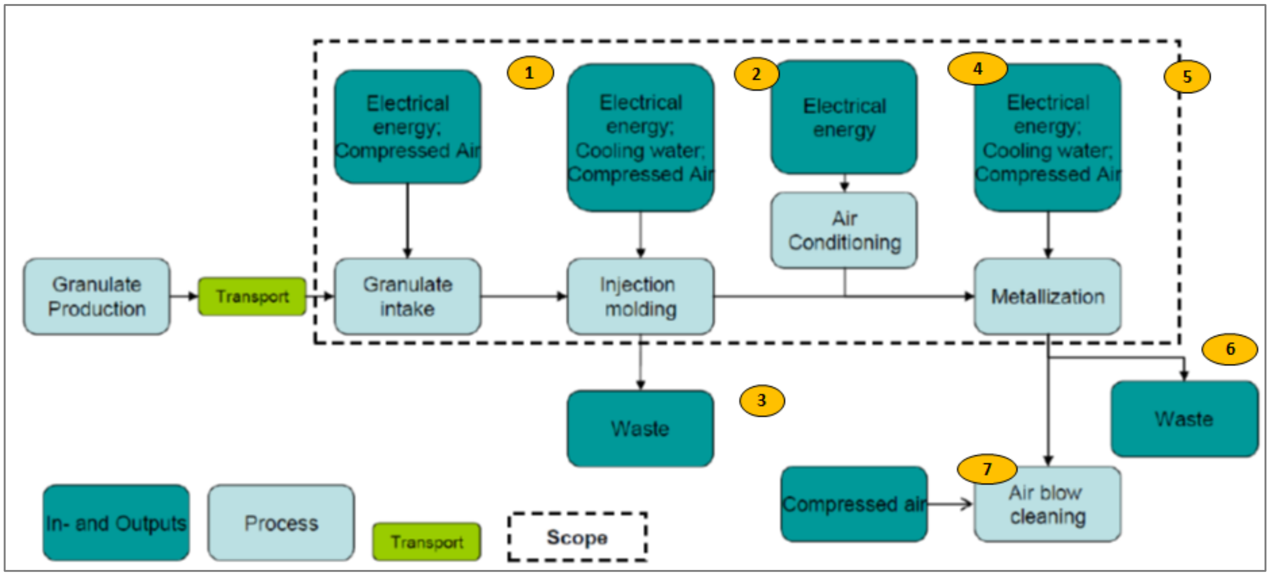


Table 48 – LCI Use phase, vehicle technical data and model parameter for halogen headlamp.

Technical data referring to car model equipped with the headlamp		
Vehicle technical characteristic	Model	2,0 - I- TSI- (110 kW)
	Mass	2018
	Emission stage	EURO 5
	Motorway per-km CO_2 emission [g/km]	234
	Mixed consumption [l/100km]	9.65
Operation	Vehicle life time [km] - dm	150,000
Analytic model [NEDC]	Mass induced fuel consumption [l/100km*100kg] - FRV_PMR [Gasoline] - fm	0.15
Mass [m]	Vehicle equipped with standard headlamp [kg]	0.38
	Vehicle equipped with innovative headlamp [kg]	0.25
Fuel density	Gasoline [kg/dm³]	0.74
Specific consumption [kg/kg fuel]	CO_2 emissions generated during the consumption of 1 kg of fuel [kg CO_2/Kg fuel] – f_{CO2}	3.12
	SO_2 emissions generated during the consumption of 1 kg of fuel [kg SO_2/Kg fuel] - f_{SO2}	0.00015

In the modeling of auxiliary module‘s life cycle, the packaging consumption have been excluded since materials are always recovered for the same purposes. In addition, the plastic landfill has not been considered in the present study since the materials under examination are both plastic.

7.5.4.2 LCA LIFE CYCLE IMPACT ASSESSMENT (LCIA)

In this section life cycle environmental impact has been calculated on the basis of data gathered during the inventory; it has been done by applying Classification and Characterisation to LCI data according to ISO 14040 standard guidelines. The results of Life Cycle Impact Assessment are reported below; this has been obtained according to CML 2001 Apr. 2016 regulations, the Primary Energy Demand (PED) category from renewable and non-renewable resources (gross cal. value) has been considered. Results are presented in Figure 68 in a form to show, for each class of environmental impact, the contribution of each life cycle stage, on the total impact, for the two design solutions, whereas the total impact percentages delta [Δ%] for each impact indicator are reported in Table 49.

Figure 68 - LCIA Results headlamp reflector.

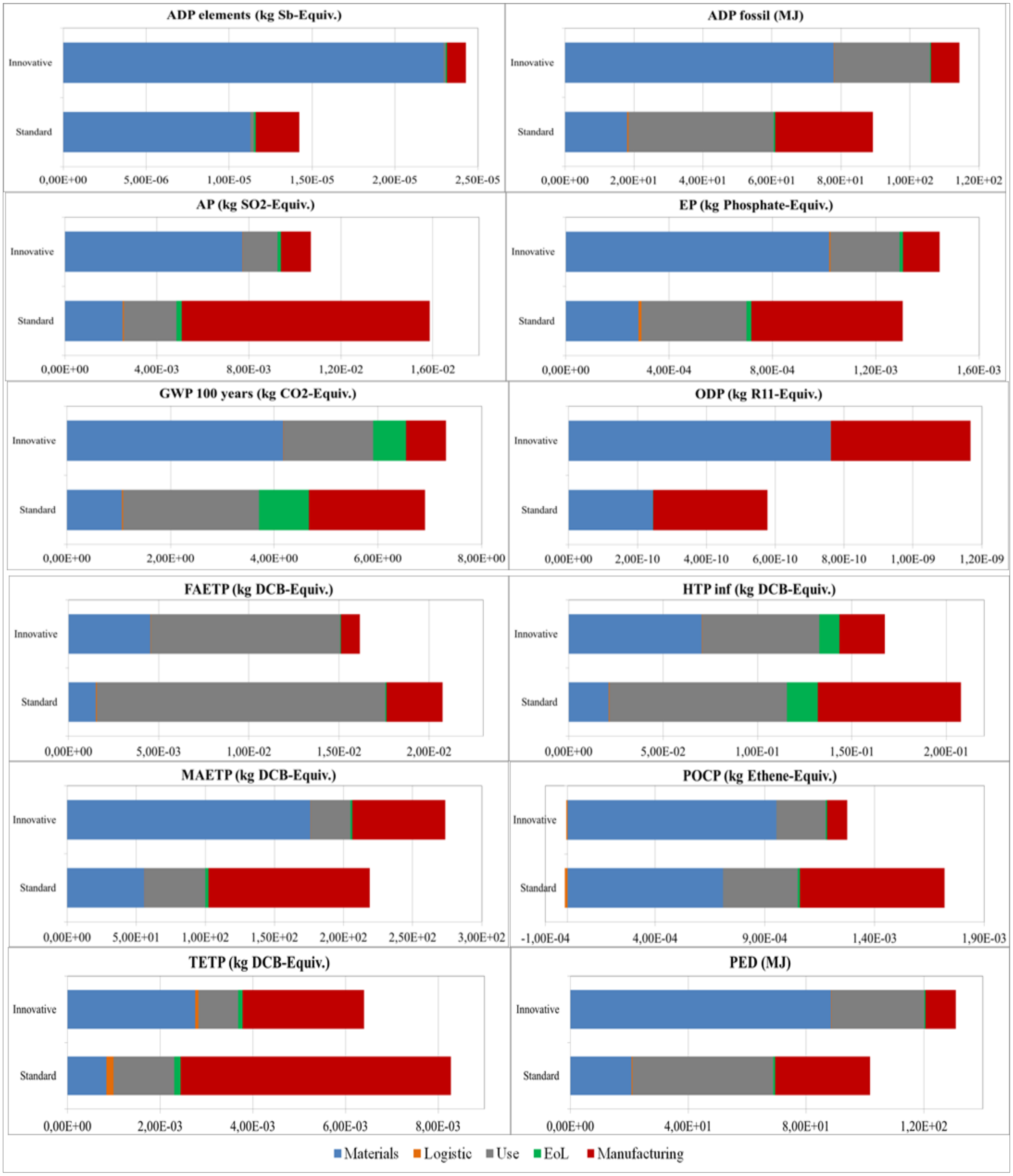


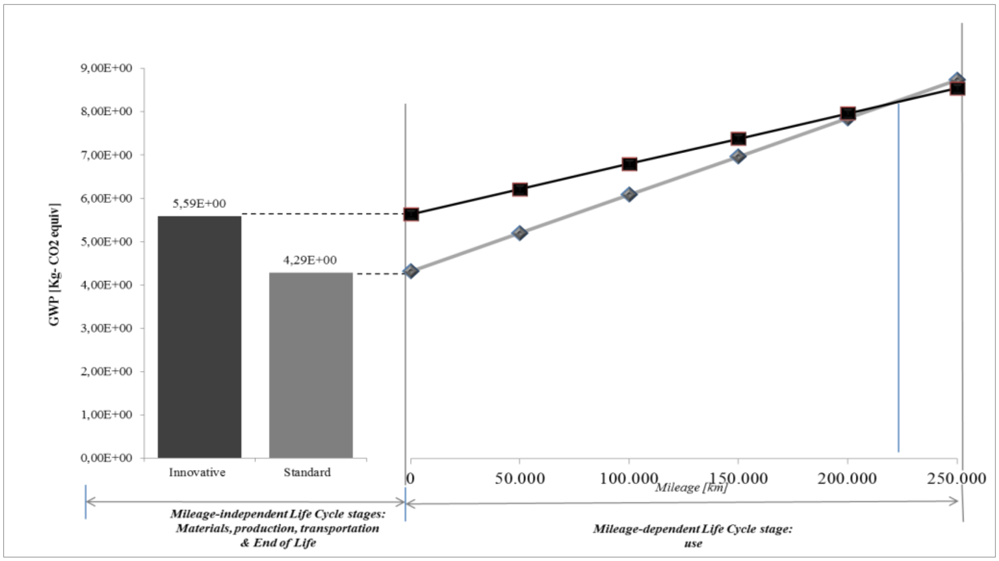
Table 49 - Headlamp total impact percentage delta decrease (-) increase ( ), worst option (W) and best option (B).

Impact categories	**Δ%**
CML2001 - Jan. 2016, Abiotic Depletion (ADP elements) [kg Sb eq.]	71%
CML2001 - Jan. 2016, Abiotic Depletion (ADP fossil) [MJ]	28%
CML2001 - Jan. 2016, Acidification Potential (AP) [kg SO2 eq.]	-33%
CML2001 - Jan. 2016, Eutrophication Potential (EP) [kg Phosphate eq.]	11%
CML2001 - Jan. 2016, Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	-22%
CML2001 - Jan. 2016, Global Warming Potential (GWP 100 years) [kg CO2 eq.]	6%
CML2001 - Jan. 2016, Human Toxicity Potential (HTP inf.) [kg DCB eq.]	-19%
CML2001 - Jan. 2016, Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	25%
CML2001 - Jan. 2016, Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	102%
CML2001 - Jan. 2016, Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	-26%
CML2001 - Jan. 2016, Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	-23%
Primary energy demand from ren. and non-ren. resources (gross cal. value) [MJ]	29%

GHG EMISSIONS BREAK-EVEN

In Figure 69 is reported the GHG emissions of CO2 over the life cycle contribution of the standard and innovative headlamp reflector. The total amount is separated according to static attribution, accounted for the upstream and downstream activities, with reference of the component operational use. Despite the reference vehicle, mileage has been assigned for all the case studies at level of 150,000km, here for GHG break-even analysis we considered a reference of 200,000km to show where the BP point fall. In fact, from the beginning the innovative solution present a high level of emissions which are counterbalanced at roughly 220,000 km of use with reference on the standard solution. In effect, the slight weight decrease effect is perceived after a great number of kilometers since the weight incidence is very low. Al 0 level axis the discrepancy is 1 kg of CO2 emissions difference.

Figure 69 – GHG break-even headlamp reflector.



7.5.4.3 LCA INTERPRETATION

In this final section, the results obtained and previously shown for each process separately are now compared and interpreted. The comparative LCA of two reflector alternatives displays rather similar results for few impact categories as GWP, EP and FAETP. Unlikely the other case studies previously analyzed, here the manufacturing contribution is particularly relevant, especially considered the impact on AP, MAETP, EP, HTP and TETP. The high manufacturing load is attributed to the BMC production due to the presence of lacquering step and styrene emissions generated during injection phase. In fact, in the manufacturing phases, lacquering (only in the thermoset reflector production) shows significant impacts in most of the categories. However, it can be concluded that from the environmental point of view the best solution between BMC and PES is strictly dependent on the impacts to be considered. Taking into account most of the environmental impact categories, including GWP, the two reflectors are comparable in a life cycle perspective, since the higher impacts associated to lacquering (manufacturing, inside MM boundaries) and use phase are counter-balanced by the burdens associated to the material eco-profile (PES)for the thermoplastic reflector (raw materials, inside the supplier boundaries). In light of manufacturing regard more insight are provided. For this reason, the impact categories where a great discrepancy is observed are analyzed in deep from manufacturing point of view. The impact categories analyzed in Figure 70and Figure 71 are: AP, GWP, EP, MAETP, POCP and TETP.

Figure 70 – Share of manufacturing impact contribution for standard (thermoset) and Innovative (thermoplastic) headlamp considering GWP, TETP and MAETP impact categories.

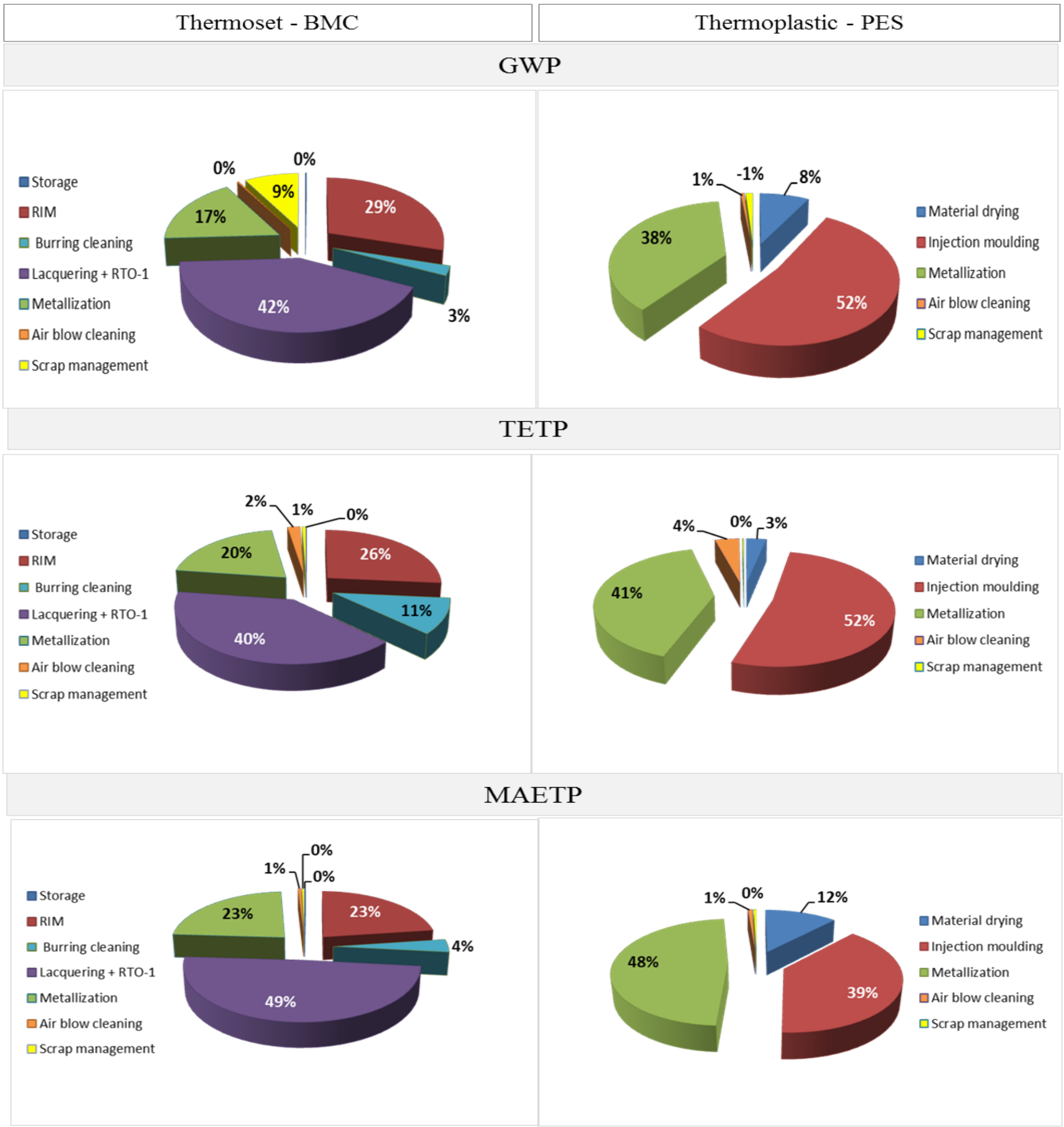
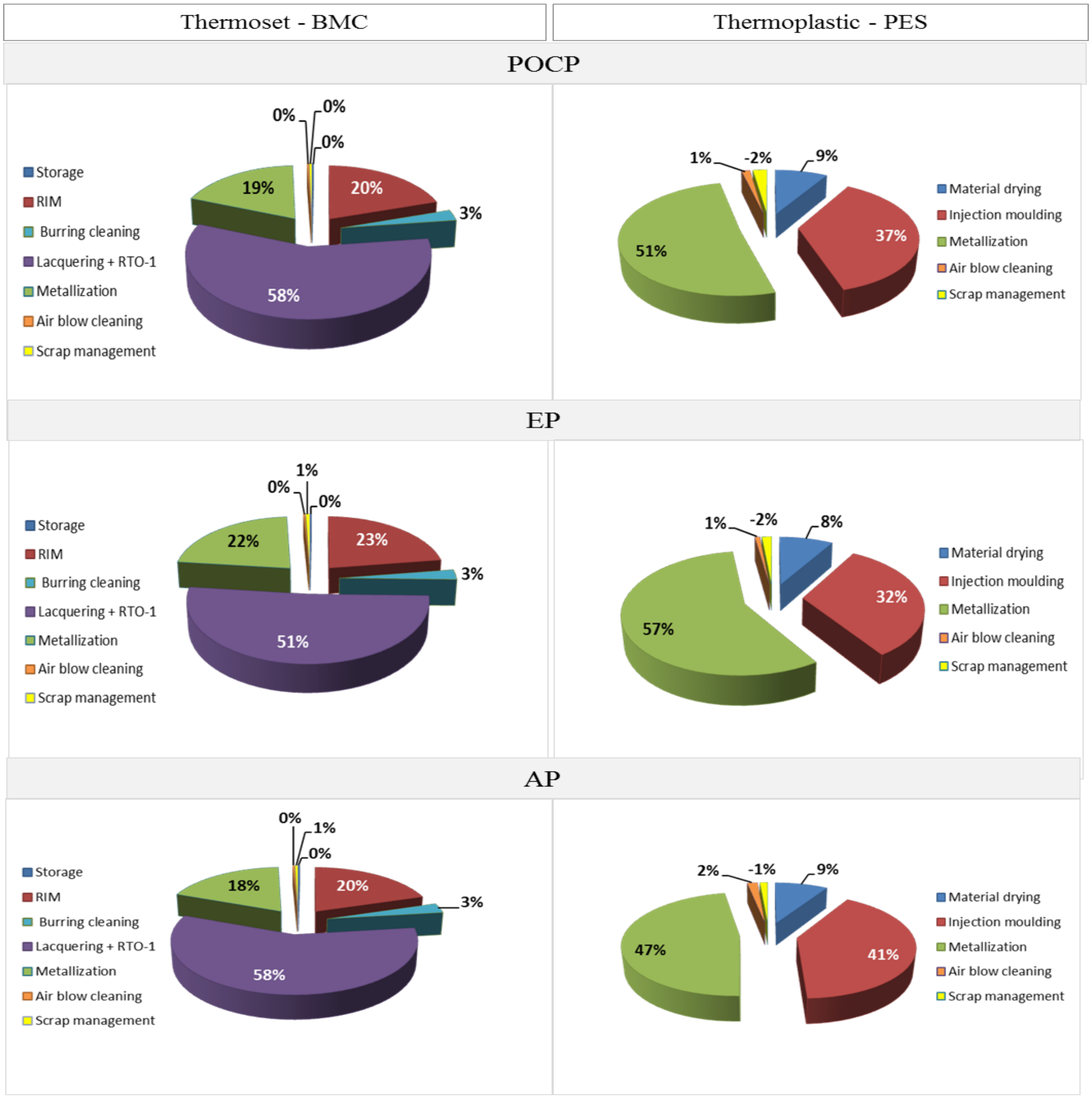


Figure 71 - Share of manufacturing impact contribution for standard (thermoset) and Innovative (thermoplastic) headlamp considering POCP, EP and AP impact categories.



7.5.5 ENVIRONMENTAL LIFE CYCLE COSTING

The following section describes the eLCC analysis of the Headlamp reflector case study.

7.5.5.1 LIFE CYCLE INVENTORY [LCI]

The unit costs are given in Table 50and according to what described in CHAPTER 5 (paragraph 5.1.2 *LCC methodology in Magneti Marelli*).

Regarding the environmental eLCC the total cost is attributed from conventional LCC with the addition of the cost derived by the CO2 emissions generated during component LC (accounting materials, manufacturing, logistic, EoL and use over 150,000 kilometers of use) and their damage cost [€/kg emissions]. The Clean Vehicles Directive 2009/33 /EC, provide valuations of specific environmental damage cost. CO_2 emissions were already calculated from LCA analysis.

Table 50 – LCC inventory headlamp reflector standard and innovative design solutions.

Life cycle phase	Flow (*per FU)	Unit cost	Source
Transports	Transports (fuel and driver) per km	1.1 €/km	*Primary data*
	Truck gross weight	10 (ton)	
	Truck payload	5 (ton)	
	Transports	1.1 €/km	
Manuf.	Electricity (cost)	0.12 €/kWh (average European)	*Eurostat, 2018*
	Electricity consumed	1.7475 kWh/FU	*Eurostat, 2018*
	Compressed air (cost)	0.016 €/Nm³	*Silventi 2018*
	Compressed air (consumed)	1.3761 Nm³/FU	*Primary data*
	Moulding machine (investment)	300.000 €	
	Robot and material drying (investment)	50.000 €	
	Metallizing (investment)	300.000 €	
	Tool (investment)	120.000 €	
Use	Gasoline	1.46 €/litre (avg European price)	*IEA, 2018*
	CO_2 emissions cost	4.00×10^{-5} €/gCO_2	*European Commission*
EoL	Electricity (price)	0.12 €/kWh (average European)	*Eurostat, 2018*
	Plastic disposal [Worst case]	0.1 €/kg	*Primary data*
	Electricity consumed for plastic separation	0,047 [Kwh/1kg plastic]	
Life cycle phase	**Flow (*per FU)**	**Unit cost**	**Source**
Transports	Transports (fuel and driver) per km	1.1 €/km	*Primary data*
	Truck gross weight (ton)	10 (ton)	
	Truck payload (ton)	5 (ton)	
Manuf.	Electricity (cost)	0.12 €/kWh (average	*Eurostat, 2018*

		European)	
	Electricity consumed	0,646 kWh/FU	*Eurostat, 2018*
	Compressed air (cost)	0.016 €/Nm^3	*Silventi 2018*
	Compressed air (consumed)	0,6825 Nm^3/FU	*Primary data*
	Moulding machine (investment)	300.000 €	
	Robot and deflashing (investment)	50.000 €	
	Lacquering (investment)	1.900.000 €	
	Building (investment)	245.000 €	
	Metallizing (investment)	300.000 €	
	Tool (investment)	150.000 €	
Use	Gasoline	1.46 €/litre (avg European price)	*IEA, 2018*
	CO_2 emissions cost	4.00×10^{-5} €/gCO_2	*European Commission*
EoL	Electricity (price)	0.12 €/kWh (average European)	*Eurostat, 2018*
	Plastic disposal [Worst case]	0.1 €/kg	*Primary data*
	Electricity consumed for plastic separation	0,047 [Kwh/1kg plastic]	

7.5.5.2 LCC IMPACT ASSESSMENT [LCIA]

In Table 51 are presented the total cost attributable to the headlamp reflector from different perspective, internalizing the cost attributable to user during vehicle use and EoL management to recover and/or disposal the relative materials. Economic assessment results are described according to the following cost categories: manufacturing, transports, use and end-of-life. 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 calculation of each contribution has been accomplished as reported below:

- for transport: the incidence of the cost per km multiplied by the total distance traveled and divided by truck payload capacity;
- for manufacturing: the cost attributable to each production item considering the contribution of investment for machine installation and energy costs;

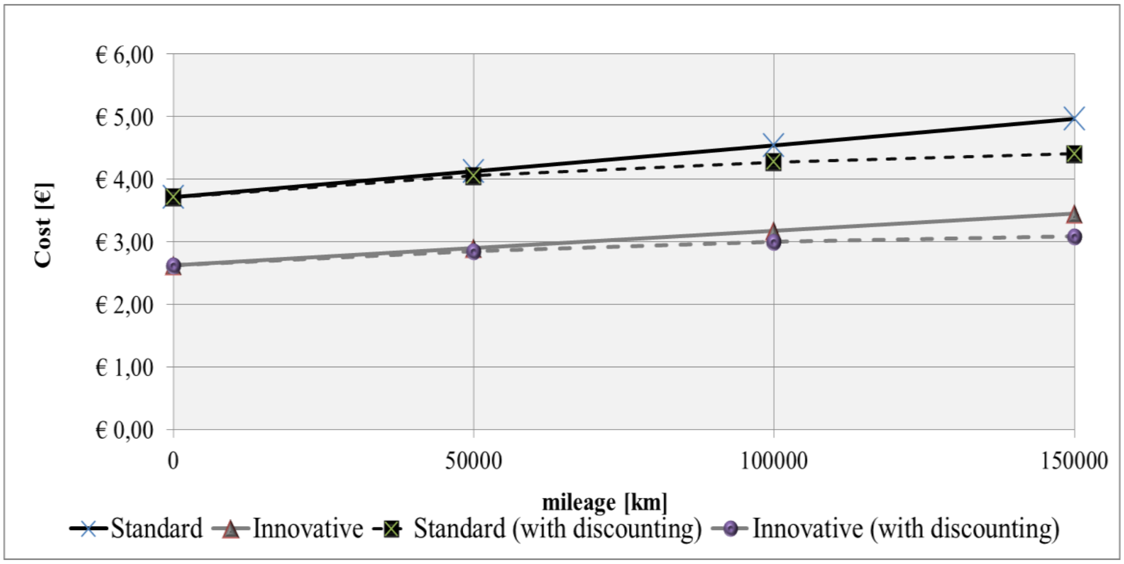
- for use: the total fuel consumption during vehicle life-time mileage of 150,000 km attributable to each component, multiplied by the average European cost of gasoline fuel;
- for EoL: the cost attributable to the disposal and/or recovery of each material flow within the dismantle line of vehicle.

Table 51 - eLCC results headlamp reflector.

Reference	Flow	Standard unit cost [€/FU]	Innovative unit cost [€/FU]
Transport	Distance travelled	*€ 0,03*	*€ 0,02*
Manufacturing	Investment	*€ 3,48*	*€ 2,54*
	Production	*€ 0,23*	*€ 0,09*
Total cost (MM perspective)		***€ 3,74***	***€ 2,65***
Use	Fuel (150.000 km)	€ 1,25	€ 0,82
	Externalities	*€ 0,0003*	*€ 0,0003*
Total cost (user perspective)		***€ 1,25***	***€ 0,82***
EoL	Materials separation	*€ 0,02*	*€ 0,01*
	Materials recovery/dispose	*€ 0,04*	*€ 0,03*
Total life cycle cost		***€ 5,05***	***€ 3,51***

Figure 72depicts the fuel consumption cost break-even analysis over the vehicle 150,000 km mileage of use. A sensitivity analysis reporting a comparison among discounting and non-discounting calculation has been accomplished. From the line chart could not be observed a break-even point since the economic convenience of the innovative headlamp production starts from production stage.

Figure 72 – Fuel cost break-even headlamp reflector.



7.5.5.3 eLCC INTERPRETATION

Environmental LCC results are presented in such a way to distinguish each life cycle cost flow attributable to the specific item. Certainly, the most discrepancy is attributed to the investment cost allocated. The new manufacturing line has revealed to be more environmentally friendly and more economic convenient. Further perceived advantages are related to the production expenditure savings, more than doubled compared to the standard line. Different consideration could be retrieved considering the different actors perspective. From MM perspective the implementation of the innovative solution means for sure a sharp production cost decrease, without considering the material cost. Further benefits are identified from user perspective, considering a cost decrease of fuel consumption, which increases proportioned to the mileage traveled. Moreover, from EoL management point of view, the less materials are processed in the EoL; the lower cost incomes are generated. To sum up, the implementation of the lighter innovative materials decrease the total cost over each LC dimensions, with more benefits related to the MM perspective.

7.6 THROTTLE BODY

This project focuses on the environmental impact assessment analysis between the employments of *two different materials profile* for the production of a specific part of an automotive component: a throttle body (here after). The method adopted is a combination of a ***Life Cycle Assessment (LCA)*** as a part of Life Cycle Sustainability Assessment (LCSA) analysis.

The purpose is to make evidence on which of the two materials profile cause the most environmental impact, considering the full product life cycle. For this purpose, the perimeter of the analysis include all the phases upstream and downstream of the MM production stage, performing in this way what is so called “cradle to grave” approach analysis.

Overall, the main goals of the project are:

- verify applicability of LCA as a supporting tool to “identify the main sustainability hotspots in the product life cycle - especially regarding its technology function during its operation on the vehicle - therefore guide strategy development” and provide elements for production decisions for TB production;
- develop data collection on environmental of the different production technologies and materials profile regarding the manufacturing of a TB;
- create a model for the environmental assessment of a specific technology and materials;
- provide guidance on different product design proposals based on environmental impact point of view.

7.6.1 GOAL OF THE STUDY

The overall scope of the study is to quantify the environmental impact of the entire TB life cycle, comparing a die-casted housing with a thermoplastic housing to be implemented in the TB. The comparison is mainly focused on the materials characterization of the two components: aluminium versus plastic. At the moment, the crucial factor in the employment of plastic materials is related their recyclability or recoverability at the dismiss phase of the vehicle. In order to better highlight the possible hotspots that could emerge from the use/replace of plastic materials for the automotive sector, the environmental modelling has involved a detailed End-of-Life analysis where the typical treatment chain is analysed in terms of energy consumptions, waste flows and final material recovery. Moreover the repercussion to the production technology change and geometry design of the TB lead by materials change of a specific part interfaced have been analysed in deep.

The main driver taken into account for improvement is *the component mass decrease* due to the lowering of the innovative material density.

The present analysis can be used to supply sustainability information to improve product performances in terms of:

- life cycle perspective to assess a balance environment point of view, among two different materials for the production of a specific component to apply at macro-level;
- find insight in the specific context of manufacturing plant;
- quantifying energy and resource intensive processes and minimizing their impact.

In order to assess the environmental impact of the innovative materials and production technology to be implemented for the manufacturing of a TB, a comparative LCA between the two different design solutions has been accomplished. The main technical difference data of the two design solutions are reported in Figure 77. The consequences of production technology variation (listed in Table 52 are: i) the change of the production technology and ii) the sub-components' weight and geometry variation.

7.6.2 COMPONENT DESCRIPTION

The throttle body (Figure 73) is a part of an air intake system, used to control the amount of air flowing into the engine. A sensor, which controls it, depending on the pressure exerted on the accelerator, opens and partializes the throttle valve and allows the passage of the exact amount of fuel gas in the intake duct, up to reseal. The rotation of the shaft, on which is screwed the valve, is achieved through an indirect regulation through a kinematic mechanical coupling. This mechanism is part of the shaft on which the valve is assembled. The exploded view of the standard TB, where all the sub-components are clearly visible, is depicted in Figure 74.

Figure 73 - a) Reference vehicle, b) front view of standard TB, c) rear view of standard TB, d) front view of innovative TB, e) rear view of innovative TB.

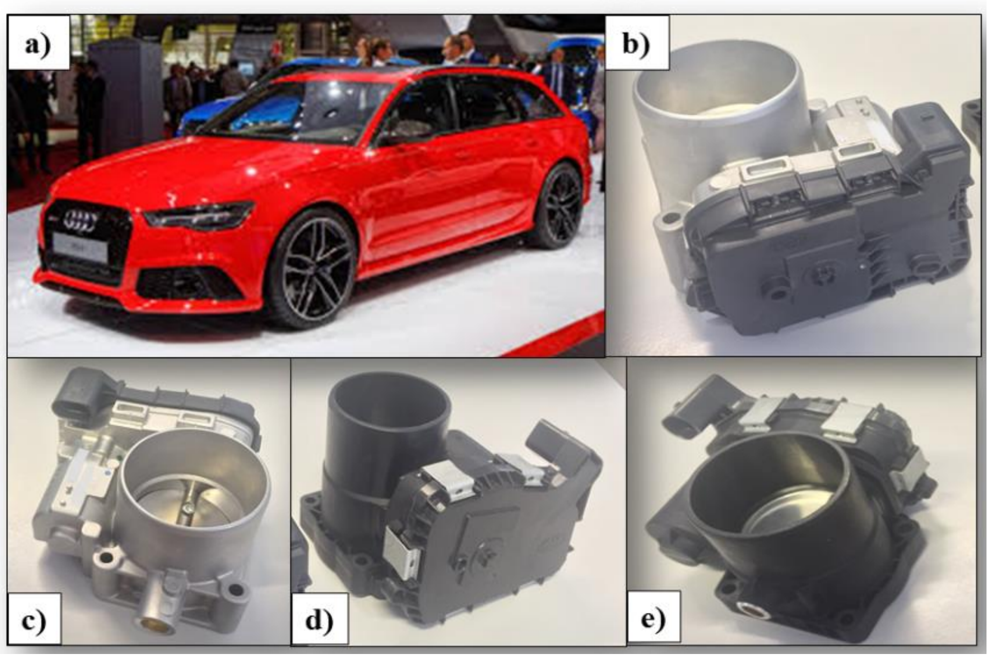
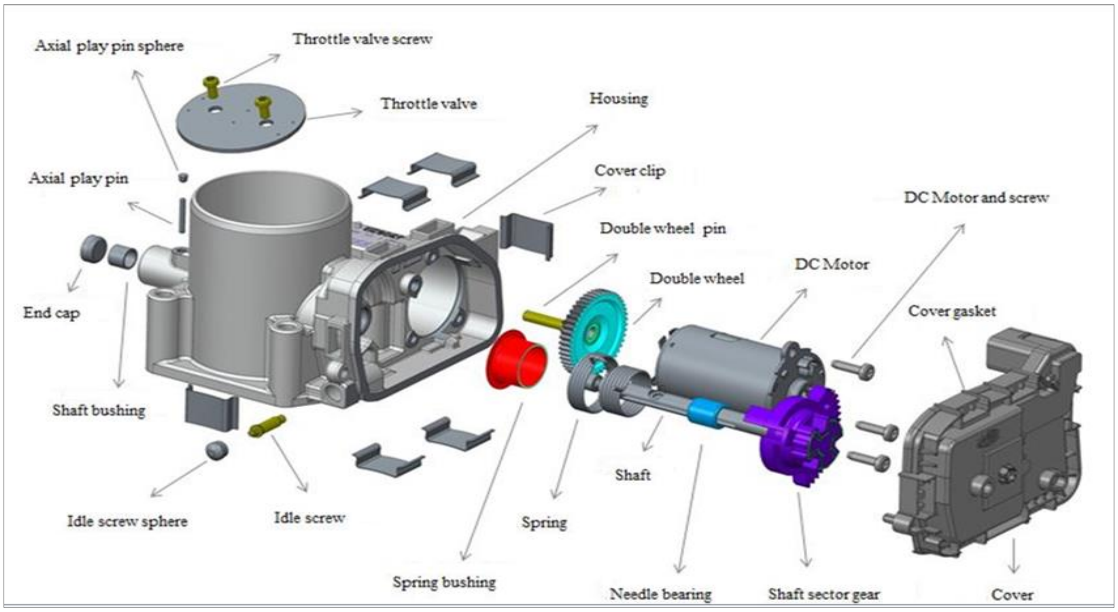
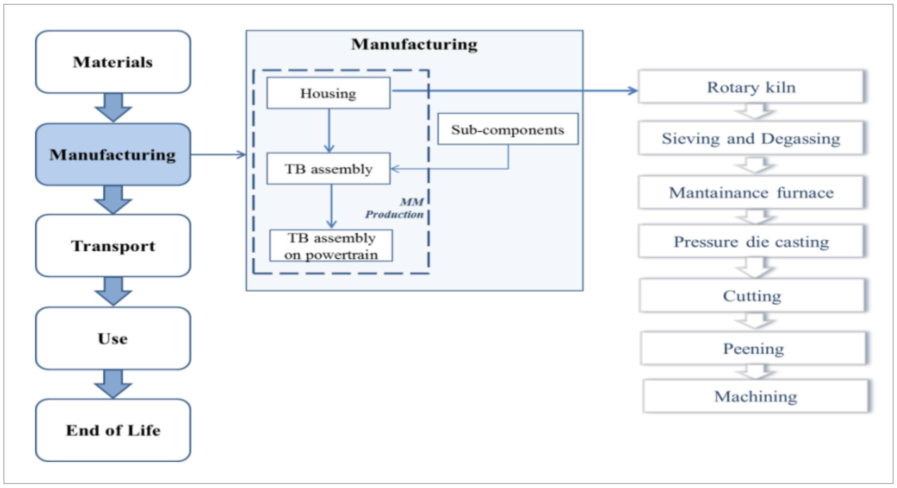


Figure 74 - Exploded view of Throttle Body using current production – Die cast Housing.



The production process of the housing is reported in Figure 75 below. The material, in ingot form, is firstly melted inside the rotary kiln, and after refining processes of sieving and degassing, is sent to the maintenance furnace to be further heated. From maintenance furnace the material is transferred by gravity, through the piping system in the injection piston and placed in the mold for the die casting. The remaining sprues - (roughly 28%) - are sent back to be melted inside the rotary kiln to start another cycle. The die cast housing is therefore sent to the plant of component assembly, where is machined in all of its compartments (with respect to tolerance requirements) for the assembly of the sub-components

Figure 75 - Life cycle phases for current solution (on the left) and manufacturing phase (on the right)



Passing to the description of the innovative TB design solution (Figure 76); it is a component realized via injection molding of PET filled with 50% on weight with fibers glass, on two inserts "Ring superlight" and "Double Wheel Pin" made up by respectively, steel and aluminum, that operate for needle bearing and bushing compartment. During the injection molding process, the compound - PET GF50 - is inserted through a hopper into the plasticizing cylinder of a press, therefor is heated, softened and then injected into the cavity of a steel mold through which takes the form. Through the temperature control system, the piece is cooled, solidifies and is extracted from the cavity. The molded housing, within the two co-stamped inserts is sent to the assembly plant to insert the remaining sub-components on it. The flowchart scheme is shown in the Figure 77 below.

Figure 76 - Exploded view of innovative throttle body design solution

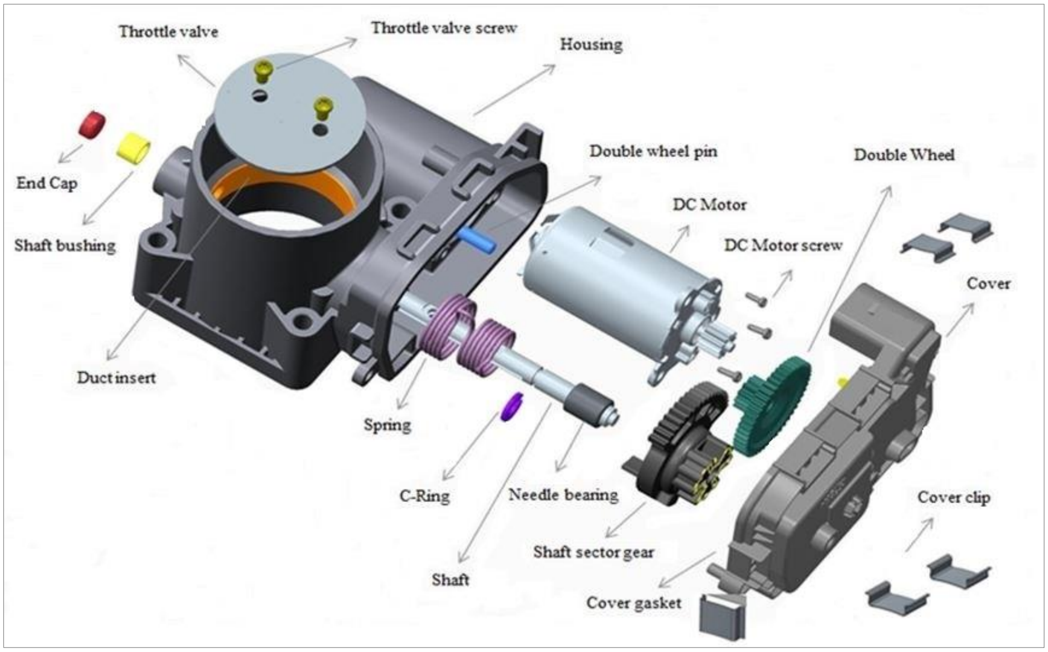
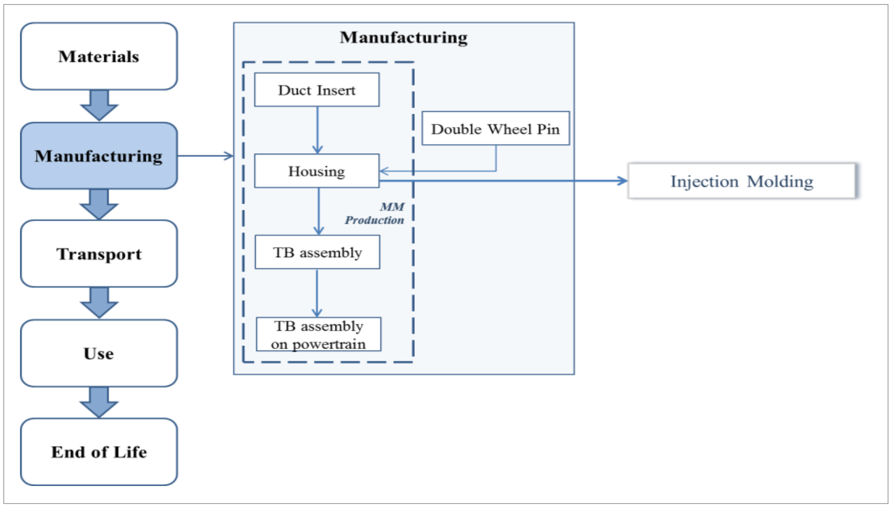
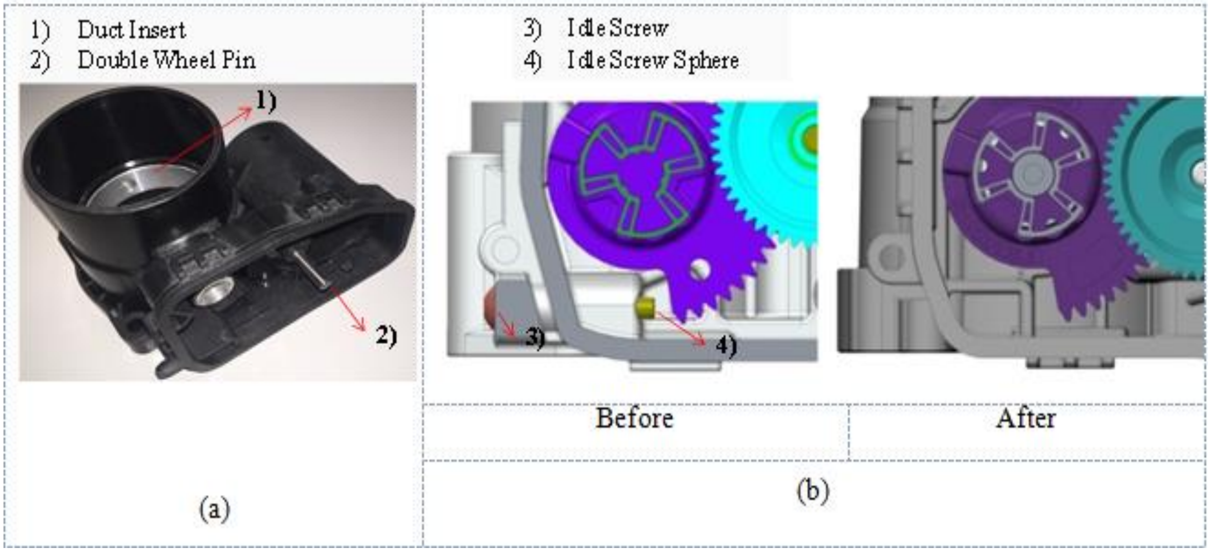


Figure 77 - Life cycle phases for innovative solution (on the left) and manufacturing phase (on the right).



The material substitution of the housing is responsible for the change in the manufacturing technology; in fact pressure die casting is replaced by injection moulding process. A part the mass reduction, additional modifications are expected thus producing an overall TB mass reduction of 22% (Figure 78). Those minor changes are the: i) introduction of co-moulded metallic duct insert into the housing; ii) repositioning of spring bushing into the housing without any support; iii) elimination of idle screw and idle screw sphere; iv) replacement of axial play pin with a C-Ring located in the shaft groove and v) introduction of a double wheel-pin over-moulded in the housing.

Figure 78 - Details about minor design modifications due to the new housing material: co-moulded metallic duct insert in the PETGF-housing TB (a); idle screw and idle screw sphere in the Aluminium-housing TB (b - Before) and PETGF-housing TB (b - After).



The list of all the sub-components, which constitute the two standard and innovative TB are reported in, is presented in Table 52.

Table 52 List of TB parts, materials and masses for the current solution (aluminium-alloy housing TB) and the new one (PETGF housing TB).

	Aluminium-alloy housing TB		**PETGF50 housing TB**	
Component	**Material**	**Mass [kg]**	**Material**	**Mass [kg]**
Axial play pin	Stainless steel	1.00 x10^{-3}	-	-
Axial play pin spher	Stainless steel	9.80 x10^{-5}	-	-
C-ring	-	-	Stainless steel	7.50 x10^{-3}
Cover	GF polybutylene - terephthalate	6.80 x10^{-2}	GF polybutylene - terephthalate	6.80 x10^{-2}
Cover clips	Stainless steel	1.80 x10^{-2}	Stainless steel	1.80 x10^{-2}
Cover gasket	Ethylene - Propylene	2.00 x10^{-2}	Ethylene - Propylene	2.00 x10^{-3}
DC Motor	Cast iron, copper, epoxy resin, copperwire, PPS	2.25 x10^{-1}	Cast iron, copper, epoxy resin, copperwire, PPS	2.25 x10^{-1}
DC Motor screws	Carbon steel	1.80 x10^{-2}	Carbon steel	2.00 x10^{-3}
Double wheel	GF Polyphthalamide - Polytetrafluorethylene	7.10 x10^{-3}	GF Polyphthalamide - Polytetrafluorethylene	7.10 x10^{-3}
Double wheel pin	Carbon steel	6.00 x10^{-3}	Carbon steel	6.00 x10^{-3}
Duct insert	-	-	Aluminium	4.70 x10^{-2}
End cap	Brass	1.00 x10^{-3}	Brass	1.00 x10^{-3}
Housing	Aluminium	4.40 x10^{-1}	PET GF	2.20 x10^{-1}
Idlescrew	Aluminium	4.30 x10^{-3}	-	-
Idlescrewsphere	Aluminium	4.30 x10^{-3}	-	-
Needlebearing	Stainless steel	7.00 x10^{-3}	Stainless steel	7.00 x10^{-3}

Shaftbushing	Stainless steel	1.90×10^{-3}	Stainless steel	1.91×10^{-3}
Spring bushing	Polyamide	8.00×10^{-3}	Polyamide	-
Spring	Stainless steel	1.20×10^{-2}	Stainless steel	1.20×10^{-2}
Shaftsectorgear	GF polybutyleneterephthalate	1.90×10^{-2}	GF polybutyleneterephthalate	1.90×10^{-2}
Shaft	Stainless steel	5.58×10^{-2}	Stainless steel	5.58×10^{-2}
Throttle valve	Aluminium	2.44×10^{-3}	Aluminium	2.44×10^{-3}
Throttle valve screw	Carbon steel	3.58×10^{-3}	Carbon steel	3.58×10^{-3}
Entire TB mass	0.86 kg		0.67 kg	

7.6.3 SYSTEM BOUNDARIES

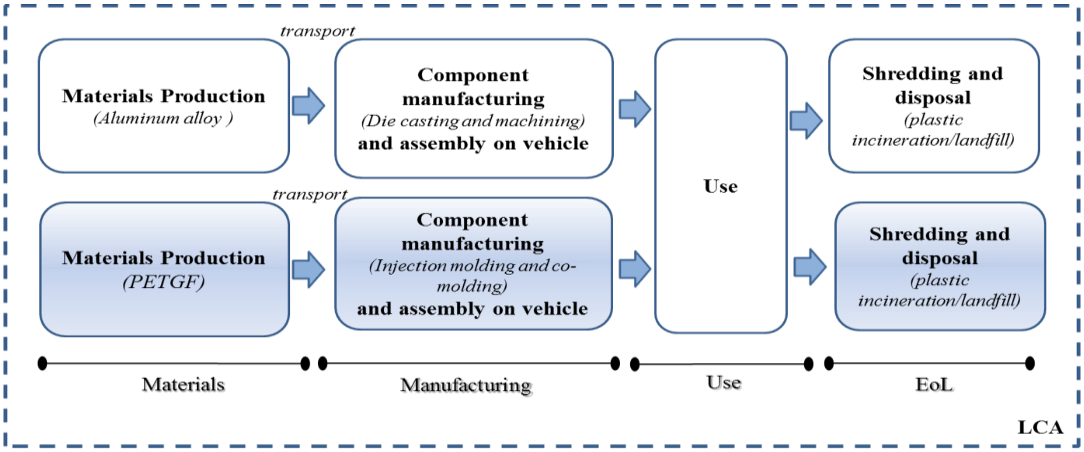
In this paragraph the product system and the system boundaries are described. Regarding the system boundary, LCA is conducted by defining product systems as models that describe the key elements of physical systems. The system boundary defines the unit processes to be included in the system. Ideally, the product system should be modelled in such a manner that inputs and outputs at its boundary are elementary flows. However, resources need not be expended on the quantification of such inputs and outputs that will not significantly change the overall conclusions of the study. The choice of elements of the physical system to be modelled depends on the goal and scope definition of the study.

The throttle body life cycle is divided into four phases:

- Materials which includes raw materials extraction and their processing;
- Manufacturing, which includes all the processes to produce the component;
- Transportation of materials to the plant of components manufacturing and transportation of the components to the plant of assembly on the powertrain of the vehicle;
- Use that includes: fuel production and tailpipe emissions;
- End of Life: consists of all the process involved to recover the materials (after vehicle dismiss) according to their typology.

The following Figure 79 characterizes throttle body life cycle phases for both scenarios, that for the initial phases of production, since the raw material of the “housing” that affect also the production process, and also some of the sub-components. Each component is analyzed through all its life cycle, according to a “cradle to gate” approach, splitting it in the following macro-phases: materials, manufacturing, logistic, use and EoL. The Functional Unit (FU) of the present analysis is an automotive throttle body, supporting and housing all the instrumentation for vehicle use, integrated within powertrain system of the Audi RS6 engine 4.0 TFSI gasoline, with a life-distance of 150000 km on 10 years.

Figure 79 – Throttle body case study system boundary.



7.6.2 LCA ANALYSIS

Here is presented the LCA methodology application on TB design solutions.

7.6.2.1 LIFE CYCLE INVENTORY (LCI)

In this sub-paragraph data collection to quantify relevant inputs and outputs of the phases which compose product life cycle is described. Where possible process parameters (materials and energy flows) were obtained by direct measurements on industrial processes and/or estimation; in the others cases assumptions from GaBi 6.115 processes database have been used. The *materials compositions* are grouped with the reference of Gabi datasets and data quality, and are reported in Table 53 and Table 54.

Table 53 - LCI material and production phase for throttle standard throttle body.

Component	Material	Technological process	GaBi modelling
Axial play pin	Stainless steel	Cold rolling	Stainless steel cold rolled coil [Metals]
Axial play pin sphere	Stainless steel	Cold rolling	Stainless steel cold rolled coil [Metals]
Cover	Polybutylene Terephthalate (PBT) Glass Fiber (GF)	Molding	Polybutylene terephthalate granulate (PBTP) [Plastics] Glass fibres [Mineral]
Cover clips	Stainless steel	Cold rolling	Stainless steel cold rolled coil [Metals]
Cover gasket	Ethylene Propylene Diene Monomer (EPDM)	Stamping	Ethylene propylene diene elastomer (EPDM) [Metals]
DC Pinion	Cast iron		Cast iron part (automotive)

Motor	Housing	Cast iron		Cast iron part (automotive)
	End cap	Cast iron		Cast iron part (automotive)
	Therminal holder	Polyphenylene sulfide granulate (PPS)		Polyphenylene sulfide granulate (PPS) [Plastics]
	Shaft	Cast iron		Cast iron part (automotive)
	Lamination	Cast iron		Cast iron part (automotive)
	Commutator	Copper		Copper (99.999%; electrolyte copper) [Metals]
	Epoxy resin	Epoxy resin		Epoxy resin [Plastics]
	Magneti	Copper		Copper wire [Metals]
DC Motor screws		Carbon steel	Cold forming Electro galvanization	Steel electro-galvanized coil [Metals]
Double wheel		Polyphthalamide (PPA) Polytetrafluorethylene (PTFE) Glass Fiber (GF)	Injection molding	Polytetrafluoroethylene granulate (PTFE) [Plastics] Glass fiber[Minerals] Nylon 6.6 granulate (PA 6.6) [Plastics]
Double wheel pin		Carbon steel	Casting and rolling	Steel billet [Metals]
End cap		Brass	Cold rolling	Brass [Metals]
Housing		Aluminium	Die casting	Aluminium ingot (secondary) [Metals] Aluminium ingot [Metals] Primary production Methane [Organic intermediate products] Oxygen liquid [Inorganic intermediate products] Calcium silicate [Minerals]
Idle screw		Aluminium	Casting and rolling	Steel billet [Metals]
Idle screw sphere		Aluminium	Casting and rolling	Steel billet [Metals]
Needle bearing		Stainless steel	Cold rolling	Stainless steel cold rolled coil [Metals]
Shaft		Stainless steel	Cold rolling	Stainless steel cold rolled coil [Metals]
Shaft bushing		Stainless steel	Cold rolling	Stainless steel cold rolled coil [Metals]
Shaft sector gear		Polybutylene Terephthalate (PBT) Glass Fiber (GF)	Injection molding	PolybutyleneTerephthalate granulate (PBTP) [Plastics] Glass fibres [Mineral]
Spring bushing		Polyamide	Injection molding	Nylon 6.6 granulate (PA 6.6) [Plastics] Polytetrafluoroethylene granulate (PTFE) [Plastics]
Spring		Stainless steel	Coiling	Stainless steel cold rolled coil [Metals]
Throttle valve		Aluminium	Stamping	Aluminium sheet [Metals]
Throttle valve screws		Carbon steel	Cold forming Electro galvanization	Steel electro-galvanized coil [Metals]

Table 54 - LCI material and production phase for throttle innovative throttle body.

Component		Material	Technological process	GaBi modeling
C-Ring		Stainless steel	Stamping	Stainless steel cold rolled coil[Metals]
Cover		PolyButylene Terephthalate (PBT)	Molding	Polybutylene terephthalate granulate (PBTP) [Plastics]
		Glass Fiber (GF)		Glass fibres [Mineral]
Cover clips		Stainless steel	Coldrolling	Stainless steel cold rolled coil [Metals]
Cover gasket		Ethylene Propylene Diene Monomer (EPDM)	Stamping	Ethylene propylene diene elastomer (EPDM) [Metals]
DC Motor	Pinion	Cast iron		Cast iron part (automotive)
	Housing	Cast iron		Cast iron part (automotive)
	End cap	Cast iron		Cast iron part (automotive)
	Therminal holder	Polyphenylene sulfide granulate (PPS)		Polyphenylene sulfide granulate (PPS) [Plastics]
	Shaft	Cast iron		Cast iron part (automotive)
	Lamination	Cast iron		Cast iron part (automotive)
	Commutator	Copper		Copper (99.999%; electrolytecopper) [Metals]
	Epoxyresin	Epoxyresin		Epoxyresin [Plastics]
	Magneti	Copper		Copperwire [Metals]
DC Motor screws		Carbon steel	Coldforming	Steel electro-galvanized coil [Metals]
			Electrogalvanization	
Double wheel		Polyphthalamide (PPA)	Injection molding	Polytetrafluoroethylene granulate (PTFE) [Plastics]
		Polytetrafluorethylene (PTFE)		Glass fiber[Minerals]
		Glass Fiber (GF)		Nylon 6.6 granulate (PA 6.6) [Plastics]
Double wheel pin		Carbon steel	Casting and rolling	Steel billet [Metals]
Duct insert		Aluminium	Stamping	Aluminium profile (processed) [Metals]
				Calciumsilicate [Minerals]
				Copperwire [Metals]
				Ferro manganese (90% Mn, low carbon) [Metals]
				Magnesiumsilicate [Minerals]
End cap		Brass	Coldrolling	Brass [Metals]
Housing		Polyethylene Terephthalate (PET)	Injection Molding	Polyethylene Terephthalate fibers (PET) [Plastics]
		Glass Fiber (GF)		Glass fibers [Minerals]
Needlebearing		Stainless steel	Coldrolling	Stainless steel cold rolled coil [Metals]
Shaft		Stainless steel	Coldrolling	Stainless steel cold rolled coil [Metals]

Shaftbushing	Stainless steel	Coldrolling	Stainless steel cold rolled coil [Metals]
Shaftsectorgear	PolyButylene Terephthalate (PBT)	Injection molding	PolyButyleneTerePhthalate granulate (PBTP) [Plastics]
	Glass Fiber (GF)		Glass fibres [Mineral]
Spring	Stainless steel	Coiling	Stainless steel cold rolled coil [Metals]
Throttle valve	Aluminium	Stamping	Aluminium sheet [Metals]
Throttle valve screws	Carbon steel	Coldforming	Steel electro-galvanized coil [Metals]
		Electrogalvanization	

Manufacturing inventory is based on the calculation within the perimeter of the component manufacturing plant during a specific time shift. In particular, housing component and TB assembly take place within MM manufacturing management. Those data are reported in Table 55 and Table 56.

Table 55 – LCI standard - housing production.

Standard housing production [reference quantity = 1 unit]		
Auxiliary materials and energy consumptions		
1) Rotary kiln	Methane [kg]	1,74E-02
	Sodium chloride [kg]	2,00E-04
2) Sieving and degassing	Methane [kg]	6,84E-04
	Nitrogen [kg]	1,33E-03
3) Maintenance furnace	Methane [kg]	1,79E-03
4) Die-casting	Electricity [MJ]	1,26E+00
5) Cutting	Electricity [MJ]	3,00E-01
6) Peening	Electricity [MJ]	1,14E-01
7) Machining	Electricity [MJ]	1,42E+00
Material balance		
1) Rotary Kiln	Aluminum ingot (+) [kg]	5,01E-01
5) cutting	Die-casted housing [kg]	4,70E-01
	Sprues (-) [kg]	2,80E-01
7) Machining	Machined housing [kg]	4,40E-01
8) Assembly	Electricity [MJ]	7,74E-01
	Compressed air [Nm³]	5,63E-02

Table 56 - LCI thermoplastic - housing production.

Innovative housing production [reference quantity = 1 unit]		
1) Injection molding	PETGF50 [kg]	2,05E-01
	Electricity [MJ]	6,96E-01
2) TB Assembly	Electricity [MJ]	6,33E-01
	Compressed air [Nm³]	4,61E-02

For the *transpor*t stage, the data collection has been conducted by truck type collection data, and distance. The company uses a logistics system that operates via milkrun, where the sub-components[39] convey from their plant of production to the closest milkrun 1 and 2. Transportation follows a path along the trail in the described in Table 57. The truck runs from France and reaches the first Milkrun where are loaded some sub-components - and then to the second to load the remaining products, up to the plant of TB assembly.

Table 57 - LCI material and production phase for throttle innovative throttle body.

Logistic - standard and innovative design					
Component	**Supplier - Milkrun 1 [km]**	**Milkrun 1 - 2 [km]**	**Milkrun 2 - MM plant of TB assembly [km]**	**Total dist. [km]**	**Means of transport, gross weight and payload capacity**
Housing	30	300	1200	1530	Diesel driven, Euro 5, cargo, 12-14t gross weight / 9,3t payload capacity and Diesel driven, Euro 5, cargo, 20 - 26t gross weight / 17,3t payload capacity
DC Motor screw	70	300	1200	1570	Diesel driven, Euro 5, cargo, 12-14t gross weight / 9,3t payload capacity and Diesel driven, Euro 5, cargo, 20 - 26t gross weight / 17,3t payload capacity
Double wheel pin	100	300	1200	1600	Diesel driven, Euro 5, cargo, 12-14t gross weight / 9,3t payload capacity and Diesel driven, Euro 5, cargo, 20 - 26t gross weight / 17,3t payload capacity
Bushing			1200	1200	Diesel driven, Euro 5, cargo, 20 - 26t gross weight / 17,3t payload capacity
Spring bushing	90	300	1200	1590	Diesel driven, Euro 5, cargo, 12-14t gross weight / 9,3t payload capacity

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[39] Except for: needle bearing, throttle valve, idle screw and DC Motor that are sent to assembly plant directly from their plant of production (sub-suppliers).

					and Diesel driven, Euro 5, cargo, 20 - 26t gross weight / 17,3t payload capacity
Spring		27	1200	1227	Diesel driven, Euro 5, cargo, 20 - 26t gross weight / 17,3t payload capacity
Axial play pin	100	300	1200	1600	Diesel driven, Euro 5, cargo, 12-14t gross weight / 9,3t payload capacity and Diesel driven, Euro 5, cargo, 20 - 26t gross weight / 17,3t payload capacity
Complete shaft	90	300	1200	1590	Diesel driven, Euro 5, cargo, 12-14t gross weight / 9,3t payload capacity and Diesel driven, Euro 5, cargo, 20 - 26t gross weight / 17,3t payload capacity
Double wheel	100	300	1200	1600	Diesel driven, Euro 5, cargo, 12-14t gross weight / 9,3t payload capacity and Diesel driven, Euro 5, cargo, 20 - 26t gross weight / 17,3t payload capacity
Complete cover	120	300	1200	1620	Diesel driven, Euro 5, cargo, 12-14t gross weight / 9,3t payload capacity and Diesel driven, Euro 5, cargo, 20 - 26t gross weight / 17,3t payload capacity
Cover clip		13	1200	1213	Diesel driven, Euro 5, cargo, 20 - 26t gross weight / 17,3t payload capacity
Throttle valve				1500	Diesel driven, Euro 5, cargo, 20 - 26t gross weight / 17,3t payload capacity
Throttle valve screw	110	300	1200	1610	Diesel driven, Euro 5, cargo, 12-14t gross weight / 9,3t payload capacity and Diesel driven, Euro 5, cargo, 20 - 26t gross weight / 17,3t payload capacity
End cap		13	1200	1213	Diesel driven, Euro 5, cargo, 20 - 26t gross weight / 17,3t payload capacity
Idle screw sphere	154	300	1200	1654	Diesel driven, Euro 5, cargo, 12-14t gross weight / 9,3t payload capacity and Diesel driven, Euro 5, cargo, 20 - 26t gross weight / 17,3t payload capacity
Axial play pin sphere	154	300	1200	1654	Diesel driven, Euro 5, cargo, 12-14t gross weight / 9,3t payload capacity and Diesel driven, Euro 5, cargo, 20 - 26t gross weight / 17,3t payload capacity
Complete				187000	Container ship, heavy fuel oil driven,

DC motor					cargo, 27500 dwt payload capacity and cargo, 20 - 26t gross weight / 17,3t payload capacity
Idle screw				1000	Diesel driven, Euro 5, cargo, 20 - 26t gross weight / 17,3t payload capacity
Needle bearing				1050	Diesel driven, Euro 5, cargo, 20 - 26t gross weight / 17,3t payload capacity

The Use stage covers the operation of the throttle body integrated within the power system of the vehicle selected. It reflects the fuel consumption linked to the mass during the life time of a vehicle.

To calculate the environmental impact imputable to the throttle body (TB) use support mass during the entire life time, it was used an analytical car consumption model, changing the default consumption of CO2 emissions values with those referred to the Audi RS6 4.0 TFSI gasoline street engine and component weight according to the parameter in Table 58.

Table 58 - LCI Use phase, vehicle technical data and model parameter for throttle body.

Technical data referring to car model equipped with the throttle body		
Vehicle technical characteristic	Vehicle model	Audi RS6 Engine EA 211 four-cylinder turbocharged and direct-injection TSI engines
	Emission stage (e.g. EURO5)	EURO5
	Vehicle mass [kg]	2010
	Motorway per-km CO$_2$ emission [g/km]	229
	Mixed consumption [l/100km]	7.5
Operation	Vehicle life time [km] - dm	150
Analytic model [NEDC]	Mass induced fuel consumption [l/100km*100kg] - FRV_PMR [Gasoline] - fm	0.15
Mass [m]	Vehicle equipped with standard throttle body [kg]	0.86
	Vehicle equipped with first innovative throttle body[kg]	0.67
Fuel density	Gasoline [kg/dm³]	0.74
Specific consumption [kg/kg fuel]	CO$_2$ emissions generated during the consumption of 1 kg of fuel [kg CO$_2$/Kg fuel] – f_{CO2}	3.12
	SO$_2$ emissions generated during the consumption of 1 kg of fuel [kg SO$_2$/Kg fuel] - f_{SO2}	0.00015

The End-of life management process of the throttle body has been modelled taking into account: the nature of the component; its materials (Table 59) and its position on the vehicle. Therefore, it was assumed that such component is not dismantled so it is shredded on the vehicle and materials are subsequently separated (Table 60). The shredding process has been modelled by means of the energy consumption according to the throttle body weight portion of incidence on vehicle total mass.

Following the ISO 22628 flowcharts, three waste flows have been modeled according to the throttle body materials composition to recover:

- Ferrous materials: shredding → aeraulic separation → magnetic separation [to separate steel];
- Non – ferrous materials : metal recovery process → screening → magnetic separation → eddy current → inductive resonance → ballistic separation [to separate aluminium];
- Others: from metal recovery process → fluff treatment in press machine [to obtain compacted fluff].

Energy consumption calculation is based on mass of component to be treated according to the EoL treatments Table 61.

Table 59 – LCI EoL throttle body BOM for standard (sx) and innovative (dx) design with material typology specification.

Standard throttle body			**Innovative throttle body**		
Component	Total weight (Kg)	Material typology	Component	Total weight (Kg)	Material typology
Aluminum housing	4,4x10-1	Non-FE metals	Plastic housing	2,10 x10-1	Thermoplastics (glass filled)
DC motor	2,25 x10-1	Non-FE metals	Duct Insert	5,65 x10-2	Non-FE metals
DCM screw	5,70 x10-3	FE metals	Double wheel pin	4,24 x10-3	FE metals
Double wheel pin	4,24 x10-3	FE metals	Complete DC motor	2,25 x10-1	Non-FE metals
Needle bearing	6,00 x10-3	FE metals	DCM screw	5,70 x10-3	Non-FE metals
Bushing	1,91 x10-3	Non-FE metals	Needle bearing	6,00 x10-3	FE metals
Spring bushing	1,20 x10-3	Thermoplastics (unfilled)	Bushing	1,91 x10-3	Non-FE metals
Double effect spring	1,20 x10-2	FE metals	Double effect spring	1,20E-2	FE metals
Axial play pin	9,00 x10-5	FE metals	C-Ring	7,00E-3	FE metals
Machined shaft	5,58 x10-2	FE metals	Metallic Insert	2,00 x10-3	FE metals

Double wheel	7,10 x10-3	Thermoplastics (glass filled)	Machined shaft	5,58 x10-2	FE metals
Vent Valve	1,00 x10-3	Elastomers	Vent Valve	5,00 x10-4	Elastomer
Overmolded cover	6,40 x10-2	Thermoplastics (glass filled)	Overmolded cover	6,40 x10-2	Thermoplastics (glass filled)
Sensor	2,00 x10-3	Non-FE metals	Sensor	2,00 x10-3	Non-FE metals
Cover clip	1,70 x10-2	FE metals	Throttle valve	2,44 x10-3	Non-FE metals
Throttle valve	2,44 x10-3	FE metals	Throttle valve screw	3,58 x10-3	FE metals
Throttle valve screw	3,58 x10-3	FE metals	End cap	1,03 x10-3	Non-FE metals
Idle screw sphere	8,90 x10-4	Non-FE metals			
Axial play pin sphere	8,90 x10-5	FE metals			
Idle screw	2,94 x10-3	Non-FE metals			

Table 60 – LCI EoL total amount of materials composition of standard and innovative throttle body.

	Standard TB	**Innovative TB**
FE metals	1,07x10-1	9,06 x10-2
Non-FE metals	6,74 x10-1	2,95 x10-1
Thermoplastics (glass filled)	7,11 x10-2	2,81 x10-1
Thermoplastics (unfilled)	1,20 x10-3	
Elastomer	2,00 x10-3	5,00 x10-4
METALS	1,07 x10-1	9,06 x10-2
NON - METALS	6,74 x10-1	2,95 x10-1
FLUFF	7,43 x10-2	2,82 x10-1
Total	**8,55x10-1**	**6,67x10-1**

Table 61 – LCI EoL energy consumption throttle body standard and innovative.

	Energy consumptions Kwh/kg	**Energy consumptions kWh/TB$_{standard}$**	**Energy consumptions kWh/TB$_{innovative}$**
METALS	4,00 x10-2	3,42 x10-2	2,67 x10-2
NON - METALS	2,50 x10-2	1,68 x10-2	7,36E-3
FLUFF	7,00 x10-3	5,20 x10-4	1,97 x10-3

Accordingly to ISO 14044, all the processes and materials related to primary data (database sources), are allocated using mass/energy reference values. To assess energy usage related to the production of each sub-component of the throttle bodies, the starting point used has been the nominal parameters of the machines used for their production and commensurate to the productivity.

In the modeling of throttle body‘s life cycle, the following consumptions have been excluded for the following reason:

- packaging consumption: since materials are always recovered for the same purposes;
- scraps generated during manufacturing: due to the negligible impact contribution attributable to each single unit [< 1% on mass reference]. However the scraps generated form materials processing are always recovered.

7.6.4.2 LIFE CYCLE IMPACT ASSESSMENT (LCIA)

In this section life cycle environmental impact has been calculated on the basis of data gathered during the inventory; by applying Classification and Characterisation to LCI data. The results of Life Cycle Impact Assessment are reported below; this has been obtained according to CML 2001 Apr. 2015 and Primary Energy Demand category from renewable and non-renewable resources (gross cal. value) has been considered. Results are presented in Figure 80 in a form to show, for each class of environmental impact, the contribution of each life cycle stage, on the total impact, for the two design solutions, whereas the total impact percentages delta [Δ%] for each impact indicator are reported in Table 62.

Figure 80 – LCIA results for throttle design solutions and EoL option according to the CML 2001 and PED impact categories.

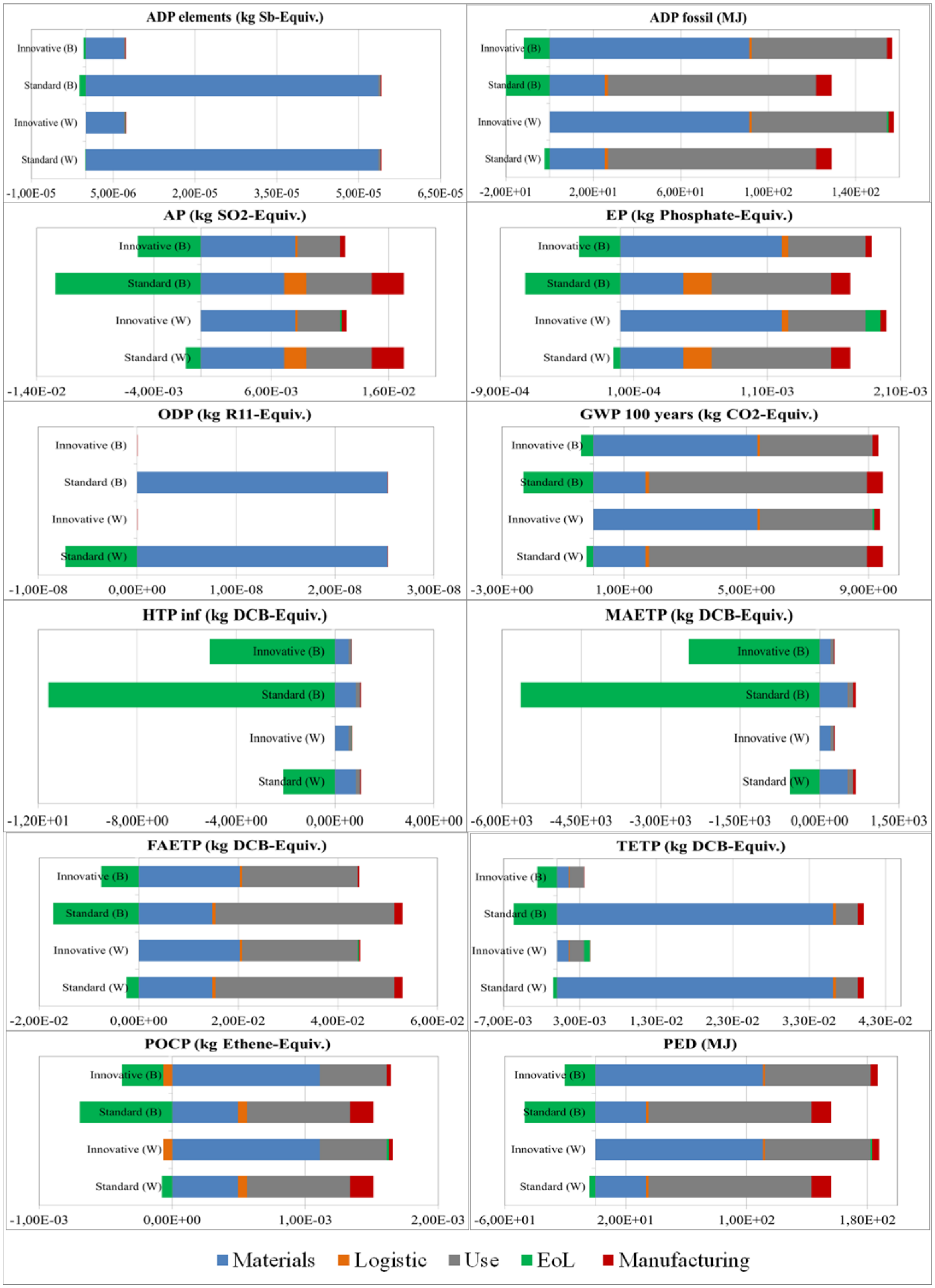


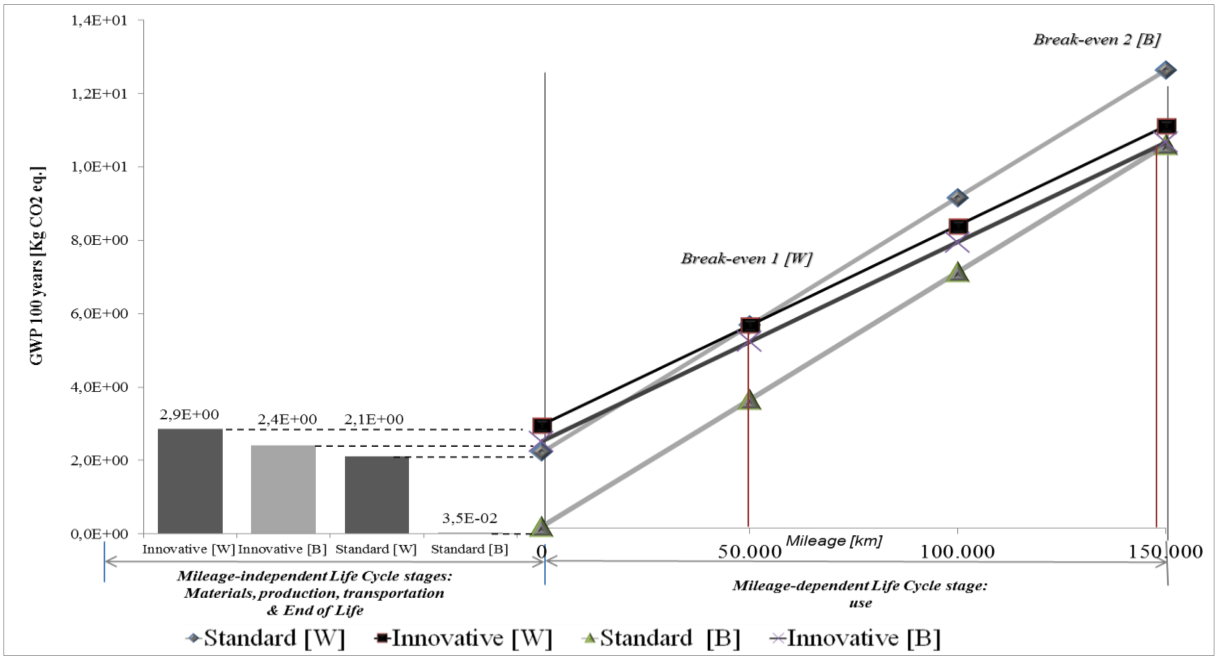
Table 62 - Throttle body Total impact percentage delta decrease (-) increase ( ), worst option (W) and best option (B).

Impact categories	Δ% (W)	Δ% (B)
CML2001 - Jan. 2016, Abiotic Depletion (ADP elements) [kg Sb eq.]	20%	21%
CML2001 - Jan. 2016, Abiotic Depletion (ADP fossil) [MJ]	-8%	1%
CML2001 - Jan. 2016, Acidification Potential (AP) [kg SO2 eq.]	21%	182%
CML2001 - Jan. 2016, Eutrophication Potential (EP) [kg Phosphate eq.]	10%	41%
CML2001 - Jan. 2016, Freshwater Aquatic Ecotoxicity (FAETP) [kg DCB eq.]	-4%	14%
CML2001 - Jan. 2016, Global Warming Potential (GWP 100) [kg CO2 eq.]	-8%	12%
CML2001 - Jan. 2016, Human Toxicity Potential (HTP inf.) [kg DCB eq.]	-419%	-83%
CML2001 - Jan. 2016, Marine Aquatic Ecotoxicity (MAETP) [kg DCB eq.]	1155%	-82%
CML2001 - Jan. 2016, Ozone Layer Depletion Potential (ODP) [kg R11 eq.]	170%	93%
CML2001 - Jan. 2016, Photochem. Ozone Creation (POCP) [kg Ethene eq.]	17%	65%
CML2001 - Jan. 2016, Terrestric Ecotoxicity Potential (TETP) [kg DCB eq.]	6%	12%
Primary energy demand from ren. and non-ren. resources (gross cal. value) [MJ]	-7%	10%

GHG BREAK-EVEN ANALYSIS

In order to assess the consumption of GHG emissions generated along component life cycle, the following break-even analysis is reported in Figure 81. The reference is two brake pedals for the fourth scenarios: standard and innovative brake pedal considering incineration [B] and landfill [W]. The graph show the emissions generated upstream and downstream of the vehicle use (static contribution) and the dynamic emissions generated during component operation within the vehicle selected (Alfa Romeo Stelvio) along different vehicle life-distance mileage. The line chart displays the variation of CO_2 emissions generated during components use within the vehicle for a life-span of 150.000 km. The lowest level (axis corresponded to 0 km) is referred to the emissions generated upstream and downstream (materials, logistic, manufacturing and end of life phases contribution). According the graphs, the most sensible variation regarding the CO_2 emissions are attributable to the operation of the component within the vehicle selected. The more the vehicle runs and the more discrepancy are observed, considering EoL worst case example: starting with 12% before vehicle use to the 29%. Instead, considering the EoL best case: starting with 11% before vehicle use to the 25%. For both cases, considering only the dynamic variation linked to the vehicle operation, after 150,000 km the discrepancy observed is about 46%, in line with component mass decrease. As shown in the diagram, production of composite housing TB involves higher impact than the aluminium one. On the other hand, thanks to mass reduction, the slope of line which represents use stage impact is lower for innovative solution with respect to the reference one. The environmental counterbalance occurs after 35,000km. Considering that usually total mileage of a car amounts to hundreds of thousands, it can be concluded that for GWP the considered innovative solution results environmentally convenient from relatively low mileages enables to achieve impact reduction of dozen percentage points and the advantage grows at vehicle mileage increasing.

Figure 81- GHG emissions break-even for brake pedal scenarios.



7.6.4.3 LCA INTERPRETATION

LCA results are presented for each impact indicators differentiating each LC contribution. The most impact is surely generated from material, use and EoL. In particular the selection among incineration and plastic landfill, cause relevant difference in terms of impact. Those differentiations are more evident in the following impact categories: MAETP, HTP, AP and EP. With regards of materials impact the innovative design show a major contribution for these categories: ADPfossil, AP, EP, GWP and FAETP. The increase of impact is due to the employment of the plastic compound, in particular the GF, which compared to the secondary aluminum worsen the effect on toxicity. On the contrary the employment of aluminium has a more negative impact on the remaining impact categories especially ODP whose is particularly influenced by the presence of aluminum. Considering use impact, the lighter innovative design decrease impact on the whole categories. Overall the implementation of the innovative solution does not moderate the TB over the total categories: the improvements are obtained only for the following categories as a whole: ADPelements, AP (considering landfill option), GWP, ODP, TETP and MAETP (considering landfill scenario).

7.7 CROSSMEMBER

This project focuses on the environmental impact assessment analysis between *different materials* for the production of a specific automotive component: a crossmember (hereafter CM). The method adopted is the ***Life Cycle Assessment (LCA)*** as a part of Life Cycle Sustainability Assessment (LCSA) analysis. The purpose is to make evidence on which of the two innovative materials cause the most environmental impact, considering the full product life cycle. For this purpose, the perimeter of the analysis include all the phases upstream and downstream of the MM production stage, performing in this way what is so called "cradle to grave" approach analysis. Overall, the main goals of the project are:

- verify applicability of LCA and LCC as a supporting tool to "identify the main sustainability hotspots in the product life cycle - especially regarding its technology function during its operation on the vehicle - therefore guide strategy development" and provide elements for production decisions for CM production;
- develop data collection on environmental impact of the different production technologies regarding the manufacturing of a CM;
- create a model for the environmental assessment of a specific technology and material;
- provide guidance on different product design proposals based on environmental impact point of view.

7.7.1 GOAL AND SCOPE

The overall scope of the study is to quantify the environmental impacts of the entire CM life cycle, comparing a standard material (stainless steel) with two innovative (aluminum and thermoplastic). The main driver taken into account for improvement is the *component lightweighting* which leads to a variation of production technology with a *simplification of the manufacturing chain*, *shortening of the total time cycle* and of *the total energy expenditure* for the production.

The present analysis can be used to supply sustainability information to improve product performances in terms of:

- life cycle perspective to assess a balance among environment point of view, different manufacturing technologies and materials for the production of a specific component to apply at macro-level;
- find insight in the specific context of manufacturing plant;
- quantifying energy and resource intensive processes and minimizing their impact.

In order to assess the environmental and economic impact of the innovative production technology to be implemented for the manufacturing of a CM, a comparative LCA between the three different design solutions has been accomplished. The main technical difference data of the design solutions are reported in Table 63. The consequences of production material variation are: i) the change of the production technology ii) the sub-components' weight and geometry variation, iii) logistic variation and iv) EoL management. The production plant of first innovative design is located within Poland, instead for the other two components are produced within Italy.

Table 63 - Technical data of crossmember design solutions.

Features	**Standard Design**	**Innovative design first solution**	**Innovative design second solution**	**Variation**
Weight (kg)	19	15.65	9.36	18% weight decrease for first innovative design; 51% weight decrease second innovative design
Parts	22 Different parts [austenitic and ferritic stainless steel *(Fe420; Fe340; Fe510 D; Fe590 FB)*	One- single structure *[Aluminum (secondary)*	Bushings (aluminum) and co-molding thermoplastic resin *[47% Vinylester resin+ 53% Caron Fibers (CFRP)]*	Sub-components and materials
Production Technology	Hot-pressing (sub-components) → Welding (assembly of sub-components) → Painting	Casting →Machining	Extrusion of aluminum; Injection co-molding	Production technology

7.7.2 COMPONENT DESCRIPTION

The McPherson front crossmember, also called *subframe,* is an auxiliary frame connected to the body at different points and linked to the lower arms through elastic bushings (Figure 82).

It is a structural component that takes part either in the suspension system and transmissions, providing support both for the anti-roll bar and steering system. It also aids in ensuring smooth suspension system operation, by guarantee proper handling and by keeping the ride aligned. In Figure 82, is reported the CM as produced for the current solution. It is constituted by several sub-components underlined here below in different colours to better distinguish all the parts. All the sub-components are listed in the Table 64where is reported for each one the portion of incidence, expressed in percentage, on the entire component. For the current production crossmember requires complex welding of multiple parts of 24 steel different parts (Table 64). The joining of all the elements take place inside an automated line, where each robots provide to weld each part on the upper and lower plates by means of arc and spot welding method. The end structure therefore undergoes an electrolytic process of cataphoresis for the final painting stage, helping in guarantee the practical quality level of welding. The figure below shows the first design concept of the Crossmember. The innovative Crossmember is constructed as a one-piece unitary structure of recycled aluminium. At the beginning the aluminum ingots are melted inside a furnace until the complete liquefaction; further, undergoes refining treatments to ensure a certain quality level. The furnace is attached to the casting machine via a feeding system, so that, the molten metal is directly pressed from the furnace chamber to the die cavity of the casting machine by a piston. The die cavity is the form from which the crossmember takes the shape. Once the metal solidifies, the die will open and the part is ejected. During a second step the one-piece is machined as to improve the surface tolerance and quality. For the Crossmember production it has been employed a composite raw material constituted of 47% Vinylester resin and 53% of Carbon Fibers Reinforced Polymer (CFRP).. The co-molded part is a composite design consisting of a rigid composite molded frame, over which are integrated bushings (produced with secondary aluminium) for the attachments during assembly on the vehicle. The composite made up of 47% of vinyl ester resin and 53% of CFRP (in granular form) is inserted into the cylinder of the moulding machine to be firstly heated, softened and further injected to the cavity from which it takes the shape.

Figure 82 – a) Reference vehicle, b) location of the crossmember within vehicle system, c) standard crossmember, d) first innovative designcrossmember, e) second innovative designcrossmember.

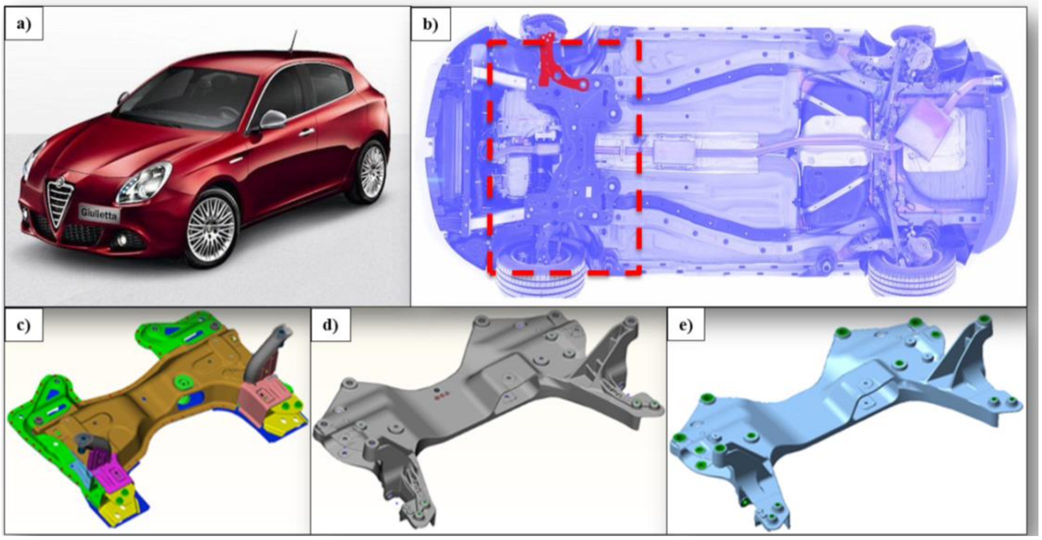


Table 64 – Standard crossmember BOM and weight.

Components	Weight [kg]	Components	Weight [kg]
Upper central plate	3,1E+00	Bracket RINF. TLC DX	6,5E-01
Lower central plate	4,6E+00	Attaching torque rod plate	1,4E-01
Bracket SX	1,8E+00	Tube plate	1,6E-01
Bracket DX	1,8E+00	Reinforcement bracket SX	1,8E-01
Reinforcement bracket PT. 1 SX	5,6E-01	Reinforcement bracket DX	1,8E-01
Reinforcement bracket PT. 1 DX	5,6E-01	Plate	3,6E-01
Control arm attaching front bracket PT. 1 SX	4,2E-01	Rear Body attachment spacer	2,6E-01
Control arm attaching front bracket PT. 1 DX	4,2E-01	Stabilizer	1,2E-01
Tube	1,4E+00	Stearing spacer	3,4E-01
Bracket SX	5,4E-01	Front Body attachment spacer.	2,6E-01
Bracket TLC DX	5,4E-01	Nut M12x1,75 RIB.	1,2E-01
Bracket RINF. TLC SX	6,5E-01	Nut M14x2 RIB.	8,0E-02

7.7.3 SYSTEM BOUNDARIES AND FUNCTIONAL UNIT

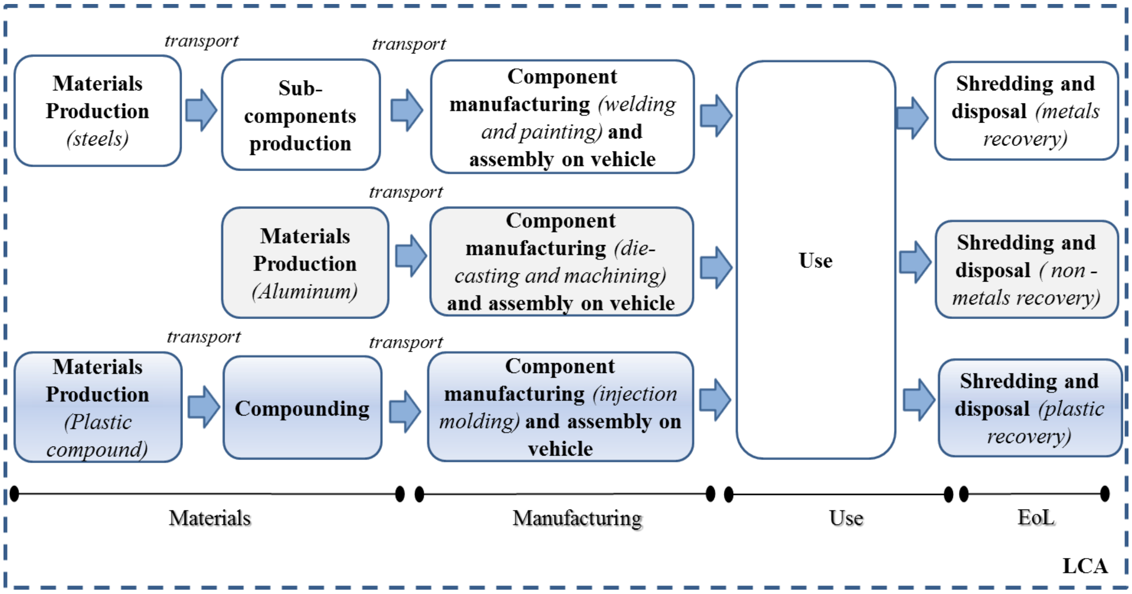
In this paragraph, the product system and the system boundaries are described. Regarding the system boundary, LCA is conducted by defining product systems as models that describe the key elements of physical systems. The system boundary defines the unit processes to be included in the system. Ideally, the product system is modelled in such a manner that inputs and outputs at its boundary are elementary flows. The choice of the elements of the physical system to be modelled depends on the goal and scope definition of the study.The three CM design options are analyzed as integrated within the suspension system of the vehicle through all its life cycle, according to a “cradle to gate” approach, splitting it in the following macro-phases: materials, manufacturing, use, end of life and transport of each phase in between.

For the present case study are considered the life cycle phase grouped according to:

- materials which includes raw materials extraction and their processing;
- manufacturing accounts for all the process involved within MM perimeter to produce the muffler;
- transportassess the impact attributed to all the shipments for the life cycle phases in between;
- useis based on component operation within the reference vehicle selected for a specific life time mileage;
- end of life: consists of all the process involved to recover/disposal of the materials (after vehicle dismiss) according to their typology.

Following Figure 83 characterizes crossmember module life cycle phases for both scenarios. The three design solution differs for the: material, manufacturing, transport and EoL.The Functional Unit (FU) of the present analysis is one*automotive crossmember* integrated within suspension system, supporting and housing all the instrumentation for vehicle use, to be mounted on aAlfa Romeo Giulietta 1.4 Turbo 105 CV gasoline for150,000 km on 10 years.

Figure 83 - Crossmember case study system boundary.



7.7.4 LCA ANALYSIS

Here is presented the LCA methodology application on CM design solutions.

7.7.4.1 LIFE CYCLE INVENTORY (LCI)

In this sub-paragraph, data collection to quantify relevant inputs and outputs of the phases, which compose product life cycle, is described. Where possible process parameters (materials and energy

flows) were obtained by direct measurements on industrial processes and/or estimation; in the others cases assumptions from GaBi 6.115 processes database have been used. In Table 65, Table 66 and Table 67 a description of modalities used to collect data is reported. The materials compositions and production are grouped with the reference of Gabi datasets and data quality. The use stage covers the operation of the CM integrated within the suspension system of the vehicle selected. It reflects the fuel consumption linked to the mass during the life time of a vehicle.
To calculate impact imputable to the component operation over the vehicle life time [150,000 km], it was used an analytical model proposed by (Koffler and Rohde-Brandeburger 2010) considering the parameters in Table 68.

The End-of life management process of the crossmember has been modelled taking into account: the nature of the component; its materials and its position on the vehicle. Therefore, it was assumed that such component is not dismantled so it is shredded on the vehicle and materials are subsequently separated. The shredding process has been modelled by means of the energy consumption according to the crossmember weight portion of incidence on vehicle total mass.

Following the flowchart in ISO 22628 three EoL management options have been modeled according to the crossmember materials composition to recover:

- *Steel crossmember*: shredding → aeraulic separation → magnetic separation [to separate steel];
- *Aluminium crossmember:* metal recovery process → screening → magnetic separation → eddy current → inductive resonance → ballistic separation [to separate aluminium];
- *Composite crossmember*: from metal recovery process → fluff treatment in press machine [to obtain compacted fluff].

Accordingly to ISO 14044, all the processes and materials related to primary data (database sources), are allocated using mass/energy reference values. Regarding the processes inside Magneti Marelli plant, due to the absence of sub-products, no allocation has been necessary. For this study, the energy and materials consumptions have been allocated considering the total amount expenditure referred to the productivity of the line, where the component is produced. In particular the line is dedicated to the production of that specific component.

Overall, in the modeling has been excluded the assembly phase of the component within vehicle suspension system, since is a manual operation for which are not required energy and/or materials expenditure.

Table 65 - LCI standard design solution crossmember [stainless steel].

	Standard Design		
Life cycle	**Specification**	**Quantity** *(per FU)*	**Process** *(GaBi; ecoinvent)*
Materials	Stainless steel [Fe420]	12.41 kg	Stainless steel cold rolled coil (430); No. 1 steel - scrap credit (open loop) (47%); EAF Steel billet /
	Stainless steel [Fe340]	1.34 kg	Stainless steel white hot rolled coil (316)
	Stainless steel [Fe510 D]	1.23 kg	Stainless steel white hot rolled coil (316)
	Stainless steel [Fe590 FB]	3.6 kg	Stainless steel white hot rolled coil (316)
	Carbon Dioxide (gaseous) - auxiliary for welding	7.3 x10-2 kg	Carbon dioxide
	Argon (gaseous) - auxiliary for welding	3.45 x 10-2 kg	Argon
	Ethanol - auxiliary for welding	4x10-5 kg	Ethanol (96%)
	copper tube (metal) - auxiliary for welding	1.03x10-4	Copper tube
	Polypropylene [PP] film (plastic) - for welding	1.7 x 10-5 kg	Polypropylene film (PP) (PlasticsEurope)
	Corrugated board boxes - auxiliary for welding	1.02x10-3 kg	Corrugated board boxes (ELCD/FEFCO)
	Steel wire rod (metals) - auxiliary for welding	8x10-2 kg	Steel wire rod (worldsteel)
	Water (deionized) - auxiliary for painting	20.5 kg	Water (deionized)
	Water (process) - auxiliary for painting	61 kg	Process water
	Wastewater treatments process - auxiliary for water disposal	81.5 kg	Waste water treatment (contains low organic load)
	Methane (gaseous) - auxiliary for painting	3.84 kg	Methane
	Coating electrodeposition mix - auxiliary for painting	4.5x10-2 kg	Coating electrodeposition mix
	Chemicals (degreasing, phosphating) - auxiliary for painting	5.8x10-3 kg	Pretreatment chemicals (degreasing, phosphating)
Manuf.	Hot-pressing sub-components	2.63 kWh	Electricity grid mix (IT)
	Welding crossmember	550 kWh	Electricity grid mix (IT)
	Painting crossmember	30 kWh	Electricity grid mix (IT)
Logistic	Total segments distance travelled	2,580 km	Truck-trailer, Euro 5, 28 - 34t gross weight / 22t payload capacity
EoL	Shredding (within drained vehicle) → Materials separation → Metals recovery	0.76 kWh	Car shredder; Steel mill scales - scrap credit (open loop); Steel rebar (23%); Electricity (IT)

Table 66 - LCI first innovative design solution crossmember [aluminum].

	First Innovative Design Concept		
Life cycle phase	**Specification**	**Quantity** *(per FU)*	**Process** *(GaBi; ecoinvent)*
Materials	a) Tempered Aluminium (secondary alloy)	15.56 kg	a)Aluminium scrap remelting & casting
	Carbon Dioxide (gaseous) - auxiliary for welding	4 x10-1 kg	Carbon dioxide
	Methane (gaseous) - auxiliary for painting	4 x10-1 kg	Methane
Manuf.	Die casting and machining	2.06 kWh	Electricity grid mix (IT)
Logistic	Total segments distance travelled	1,000 km	Truck-trailer, Euro 5, 28 - 34t gross weight / 22t payload capacity
EoL	Shredding (within drained vehicle) → Materials separation → Non-metals recovery	1.17 kWh	Car shredder; Aluminium auto roads - scrap credit (open loop) (32%); Aluminium clean scrap remelting & casting (2010); Electricity grid mix

Table 67 - LCI second innovative design solution crossmember [plastic].

	Second Innovative Design Concept		
Life cycle phase	**Specification**	**Quantity** *(per FU)*	**Process** *(GaBi; ecoinvent)*
Materials	Aluminum (secondary)	1.36 kg	Aluminium extrusion profile
	Vinylester resin	3.76 kg	Vinyl ester
	Carbon fibers	4.24 kg	Carbon Fiber (CF; from PAN)
Manuf.	Extrusion for bushings production	18.3x10-2 kWh	Electricity grid mix (IT)
	Injection co-molding	12.2 kWh	Electricity grid mix (IT)
Logistic	Total segments distance travelled	2,380 km	Truck-trailer, Euro 5, 28 - 34t gross weight / 22t payload capacity (Gabi)
EoL	Shredding (within drained vehicle) → Materials separation → Plastic Landfill	0.44 kWh	Car shredder ;Waste incineration of plastics (Nylon 6, Nylon 66, PAN); Electricity grid mix (IT)
	Shredding (within drained vehicle) → Materials separation → landfill/plastic incineration	0.44 kWh	Car shredder ;Plastic waste on landfill; Plastic incineration; Electricity grid mix

Table 68 - LCI Use phase, vehicle technical data and model parameter for crossmember.

Technical data referring to car model equipped with the crossmember		
Vehicle technical characteristic	Model	Alfa Romeo Giulietta 1.4 Turbo gasoline 105 CV (77.2 kW)
	Emission stage	EURO 5
	Mass [kg]	1280
	Motorway per-km CO_2 emission [g/km]	149
	Mixed consumption [l/100km]	5.3
Operation	Vehicle life time [km] - dm	15
Analytic model [NEDC]	Mass induced fuel consumption [l/100km*100kg] - FRV_PMR [Gasoline] - fm	0.15
Mass [m]	Vehicle equipped with standard crossmember support [kg]	19
	Vehicle equipped with first innovative crossmember [kg]	15.65
	Vehicle equipped with second innovative crossmember [kg]	9.36
Fuel density	Gasoline [kg/dm³]	0.74
Specific consumption [kg/kg fuel]	CO_2 emissions generated during the consumption of 1 kg of fuel [kg CO_2/Kg fuel] – f_{CO2}	3.12
	SO_2 emissions generated during the consumption of 1 kg of fuel [kg SO_2/Kg fuel] - f_{SO2}	0.00015

7.4.4.2 LCA LIFE CYCLE IMPACT ASSESSMENT (LCIA)

In this section life-cycle environmental impact has been calculated on the basis of data gathered during the inventory; by applying Classification and Characterisation to LCI data. The results of Life Cycle Impact Assessment are reported below; this has been obtained according to CML 2001 Apr. 2015 and Primary Energy Demand category from renewable and non-renewable resources (gross cal. value) has been considered. Results are presented in Figure 80 in a form to show, for each class of environmental impact, the contribution of each life cycle stage, on the total impact, for the two design solutions, whereas the total impact percentages delta [Δ%] for each impact indicator are reported in Table 62

Figure 84– LCIA results for throttle design solutions and EoL option according to the CML2001 and PED impact categories.

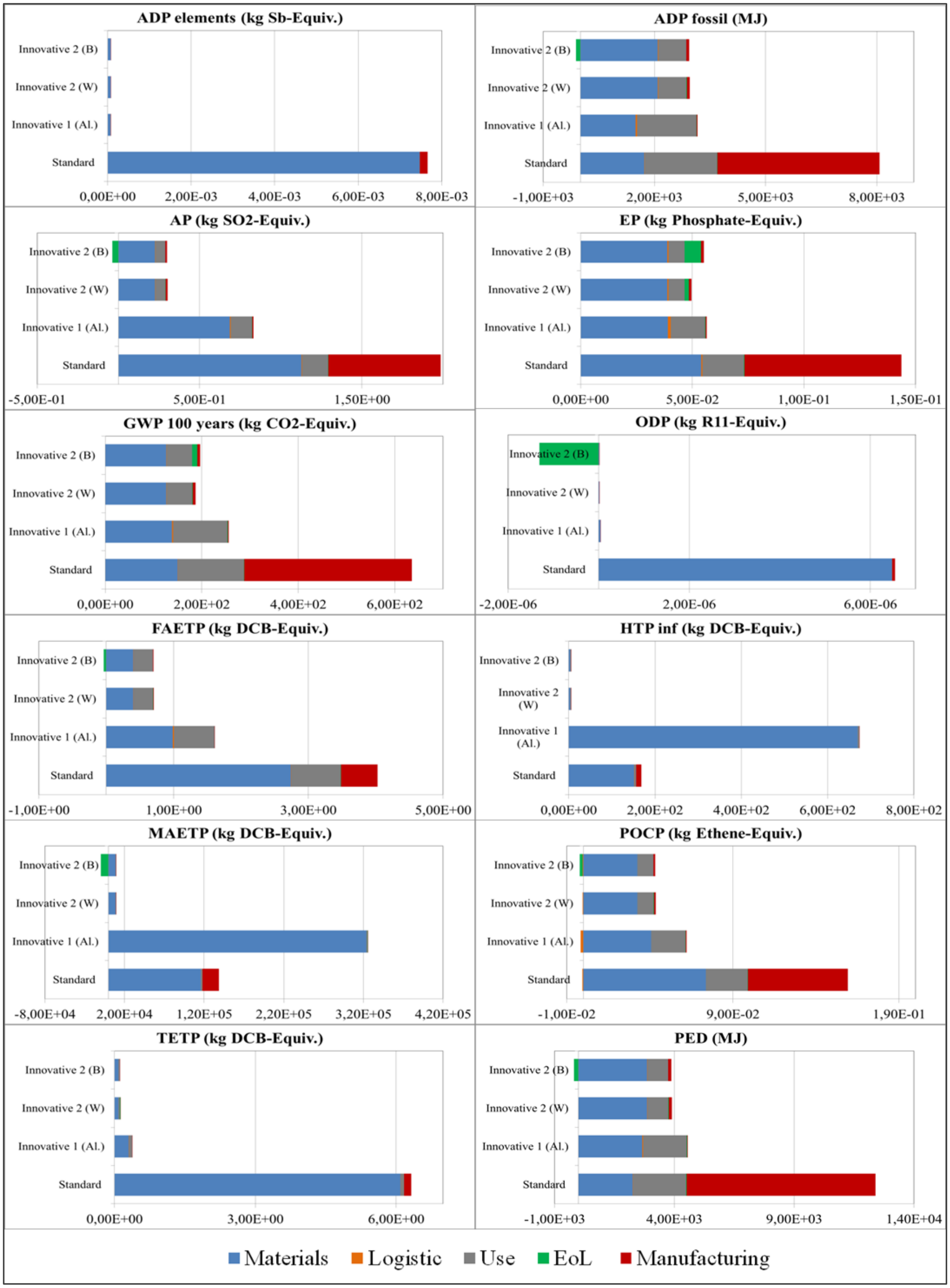


Table 69- Crossmember total impact percentage delta decrease (-) increase ( ).

Impact categories	Δ% (Al.)	Δ% (plastic W)	Δ% (plastic B)
Abiotic Depletion (ADP elements) [kg Sb eq.]	-99%	-99%	-99%
Abiotic Depletion (ADP fossil) [MJ]	-62%	-63%	-65%
Acidification Potential (AP) [kg SO2 eq.]	-58%	-85%	-87%
Eutrophication Potential (EP) [kg Phosphate eq.]	-61%	-65%	-61%
Freshwater Aquatic Ecotoxicity Pot. (FAETP)[kg DCB eq.]	-61%	-83%	-84%
Global Warming Potential (GWP 100) [kg CO2 eq.]	-61%	-70%	-69%
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	300%	-97%	-97%
Marine Aquatic Ecotoxicity Pot. (MAETP) [kg DCB eq.]	135%	-93%	-100%
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	-99%	-100%	-120%
Photochemical. Ozone Creation Potential (POCP) [kg Ethene eq.]	-63%	-73%	-74%
Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	-94%	-98%	-98%
Primary energy demand from ren. and non-ren. resources [MJ]	-64%	-68%	-70%

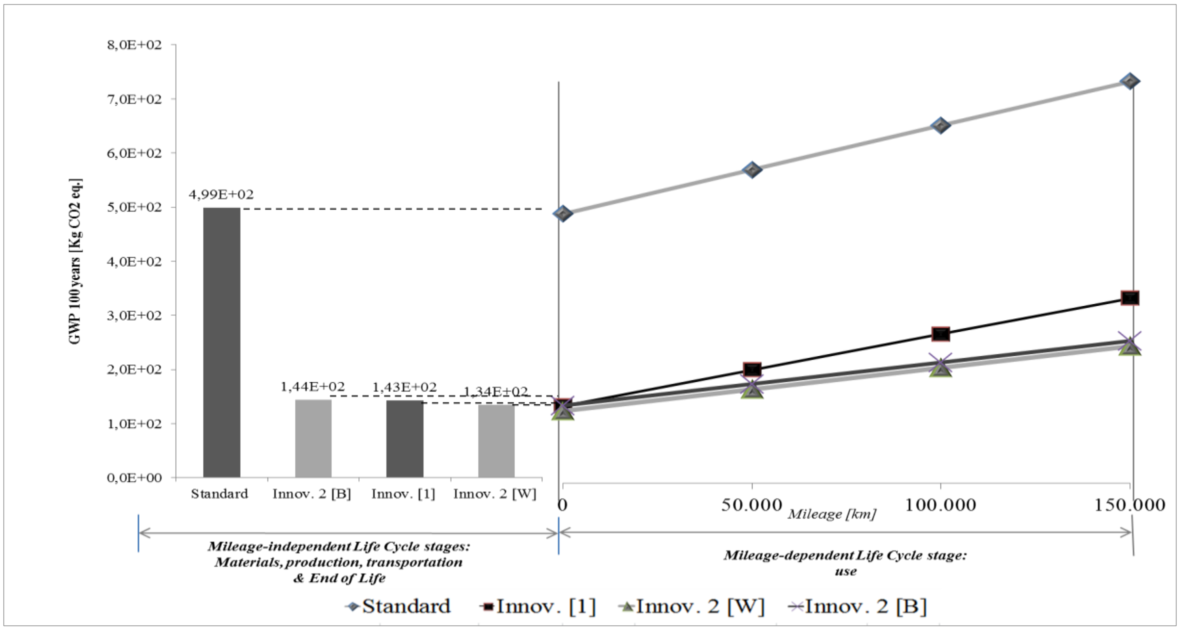
GHG BREAK-EVEN ANALYSIS

In order to assess the consumption of GHG emissions generated along component life cycle, the following break-even analysis is reported in

Figure 56. The reference for the fourth scenarios are: standard CM (steel), first innovative (aluminum), second innovative solution (composite) considering landfill [W] and incineration [B] option. The graph show the emissions generated upstream and downstream of the vehicle use (static contribution)and the dynamic emissions generated during component operation within the vehicle selected along different vehicle life-distance mileage. The line chart displays the variation of CO_2 emissions generated during components use within the vehicle for a life span of 150,000 km. The lowest level (axis corresponded to 0 km) is referred to the emissions generated upstream and downstream (materials, logistic, manufacturing and end of life phases contribution). According the graphs, the most sensible variation regarding the CO_2 emissions are attributable to the operation of the component within the vehicle selected. The more the vehicle runs and the more discrepancy are observed. From the very beginning, the standard solution generates about 5 times more emissions compared to the alternative. The lowest emissions are attributed to the composite CM considering landfill case. Before vehicle use the discrepancy between the CM aluminum, do not exceed 9 kg. However, it is important to underlying the amount of emissions generated in the CM composite considering the two EoL option: if the incineration option is selected, the generation of CO2 emissions increase of 7% with reference of landfill alternate.

In conclusion, looking at the whole LC, the highest emissions are generated by the CM standard, while the lowest by CM composite (second alternative).

Figure 85 – GHG emission break-even crossmember.



7.4.4.3 LCA INTERPRETATION

In this final section, the results obtained and previously shown for each process separately are now compared and interpreted. Results are displayed in such a way to show the total impact contribution differentiated for the single LC. From the results emerged that environmental impacts depend mainly on raw materials eco profiles and use phase so the choice of material becomes significant both from the point of view of the extraction and production of raw material both from the point of view of final weight reduction resulting. Nevertheless, a relevant impact contribution is related to the manufacturing stage for the standard solution. The manufacturing of standard CM extremely impact ADPfossil, AP, EP, POCP and PED. The reason behind is due to the production of electricity, which require consumption of abiotic elements and generate harmful gases. For all the impact categories the standard solution shows a higher impact for each issue. On the contrary, the second innovative scenario has the lowest impact among all the indicators. Another matter of fact is the selection of aluminium-base product, which worsens the effect on MAETP and HTP. No sensible variations are perceived from the selection of alternative incineration and landfill scenario with the exception of GWP and ODP.

7.8 DASHBOARD

The project deals with the sustainability assessment of the dashboard(hereafter DSB) during its whole life cycle, by means of the Life Cycle Sustainability Assessment (LCSA) application, as methodology to assess environmental, economic and social impacts along a product life cycle. The main goals of the project are:

- verify applicability 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;
- as far as social assessment concerned, to verify applicability of the approach proposed within the initiative of "Roundtable for Product Social Metrics";
- develop data collection on environmental, economic and social sphere.

The study regards the assessment of the standard component design therefore the main results regard the methodology applicability in terms of data availability, indicators relevance and appropriateness, and results presentation and interpretation. Outcomes in terms of component sustainability could be retrieved mainly concerning environmental and economic assessment; however, more insights could be obtained from the comparative analysis. According to the point of view of the involved companies, the value added of the LCSA is foreseen 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 cannot only check the three pillars of sustainability in the same time but the integration and finding the best compromise among them*".A part of the present study, in particular outcomes related to environmental and economic assessments, has been published in a scientific journal in the following paper: "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".

7.8.1 GOAL AND SCOPE DEFINITION

The scope of the present study is to assess the environmental, economic and social impacts of a dashboard mounted on a Alfa Romeo Mito gasoline according to the three sustainability dimensions: environmental, economic and social. In particular, *a standard material* used for the production of the dashboard is compared with *an innovative*, according to the whole life cycle perspective. The main drivers taken into account for improvement is the component *lightweighting*, due to the lower density of the innovative material which also involves the reduction of the cycle time for the production of the bottom insert. This LSCA can be used to supply sustainability information to improve product performances in terms of:

- “life cycle” perspective to assess a balance among environment, economic and social point of view;
- demonstrating a commitment by manufacturers to stakeholders for the responsible development of MM products, and assess stakeholders performance on environmental, economic and social behaviours;
- quantifying energy and resource intensive processes and minimizing their impact;
- identifying cost savings for the manufacturer and consumer.
- develop an evaluation of impacts and risks to human health, the environment, and society from the local to national and global scales.

The perspective is generally defined only for the LCC, while for the LCA and S-LCA it is less clearly specified. In this study, the perspective considered is of the manufacturer at the refining process and so Magneti Marelli in the calculation of conventional cost, whereas the environmental LCC included user and ELV actor perspective. Societal LCC consider the community as external actor. In order to assess the environmental, economic and social impact of the innovative material to be implemented for the manufacturing of a dashboard, a comparative LCA , eLCC and S-LCA between the two different design solutions has been accomplished. The main technical difference data of the two design solutions are reported in

Table 70. The consequences of material variation are: i) the change of the production technology referred to the molding step (with a shortening of the time cycle of 20%) and ii) the lower insert weight decrease with no a geometry variation.

Table 70 – Technical data of dashboard design solutions.

Features	Standard	Innovative	Variation
Weight (kg)	4.722	3.962	16% weight reduction
Parts	a) Lower insert [Polypropylene reinforced with 25% talc (*PP 65.40 U)]*	a) Lower insert [Polypropylene reinforced with 23% Hollow glass spheres *(PP 23HGS)]*	Reinforced filler change
	b) Foam [Isocyanate and Polyol]	b) Foam [Isocyanate and Polyol]	-
	c) Upper mantle [Thermoplastic polyolefin (TPO)]	c) Upper mantle [Thermoplastic polyolefin (TPO)]	-
Production technology	Molding → shredding → plasma treatments; thermoforming; foarming → milling → laser treatment	Molding → plasma treatments; thermoforming; foarming→ milling→ laser treatment	Shortening time cycle (20%) and addition of *"shredding"* in the standard production

7.8.2 COMPONENT DESCRIPTION

The component analyzed in this study is a dashboard, which takes part in the interior part and placed in Alfa Romeo Mito 955 (Figure 86). The DSB is constituted by different layers. From the section in Figure 87, it can be clearly distinguish the three layers that make it up: the bottom insert, the intermediate foam and the upper mantle. The production starts with the injection molding for the production of the lower insert. The material, consisting of reinforced polypropylene in a granular form, is inserted inside the hopper, and transferred by gravity through the channel in the injection piston where it is melted and injected into the mold. The piece is cooled, solidified and then removed from the cavity. Further the lower insert undergoes a surface treatment with atmospheric plasma activation, required for the following process of foaming. The gas at atmospheric pressure is energized by the application of the high voltage so as to generate the plasma. The compressed air forces the plasma out of the nozzle. An automated robot emits the beam which encompasses the entire surface of the body. The upper part of the DSB, the mantle is the only visible layer from the outside; it is produced via thermoforming process under vacuum. The raw material consists of TPO film, is preheated and then it is laid on the mold, where by suction, copies all the sinuosities of the mold. Following the mantle is cooled by means of fans. Subsequently they are inserted in the housing of the machine for the foaming: the lower mantle on top seat and the upper mantle on the lower one. The two parts of the mold where are located the two inserts are constructed so that, once closed the housing, they are perfectly superimposed, with a cavity in between where, by means of pipes, is inserted the foam of polyol and isocyanate. The perimeter of the insert foam is milled to be perfectly defined outside for assembly on the vehicle and at the end undergoes a laser processing. Imagines of the semi-products are reported in Figure 87.

Figure 86 - a) Reference vehicle, b) dashboard location within the vehicle.

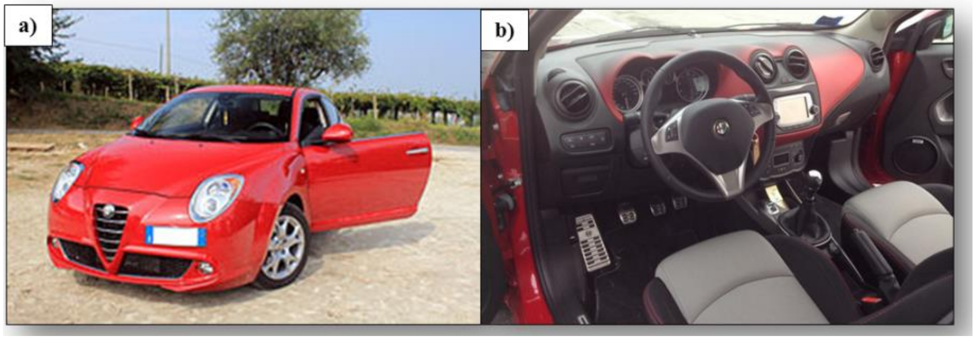
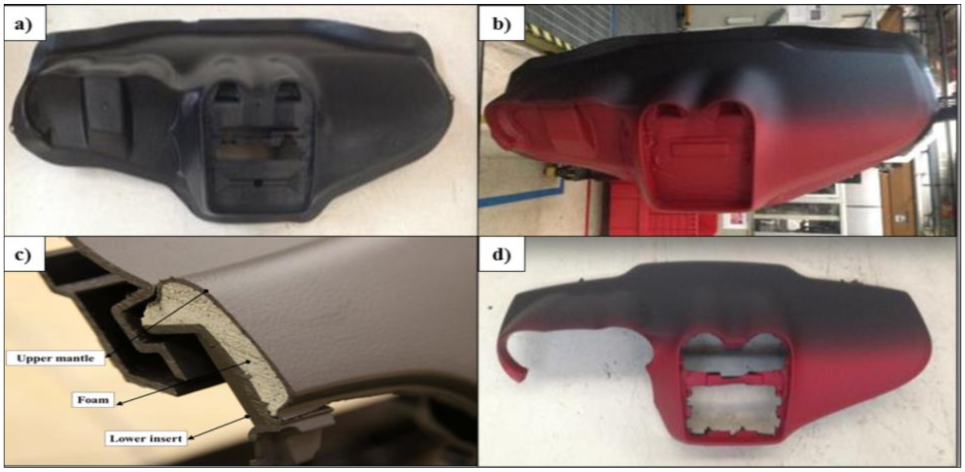


Figure 87 – a) Lower insert (standard), b) thermoformed mantle, c) dashboard section, d) final component as produced.



7.8.3 SYSTEM BOUNDARIES AND FUNCTIONAL UNIT

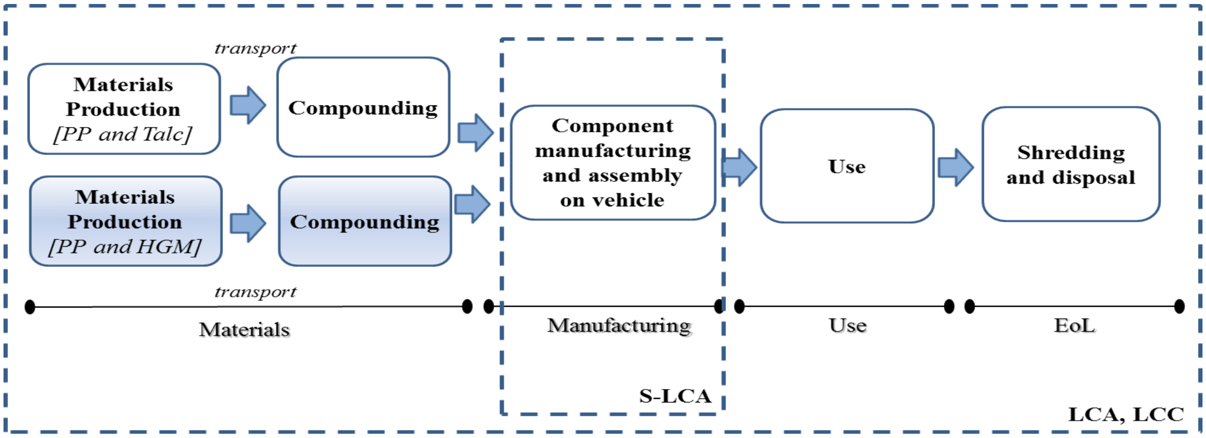
In this paragraph the product system and the system boundaries are described (Figure 88). Regarding the system boundary, LCA and LCC are conducted by defining product systems as models that describe the key elements of physical systems. The system boundary defines the unit processes to be included in the system. Ideally, the product system is modelled in such a manner that inputs and outputs at its boundary are elementary flows. The choice of the elements of the physical system to be modelled depends on the goal and scope definition of the study.The two DSB design options are analyzed as integrated within the interior panel system through all its life cycle, according to a “cradle to gate” approach, splitting it in the following macro-phases: materials, manufacturing, and use, end of life and transport of each phase in between.

For the present case study are considered the life cycle phase grouped according to:

- materials which includes raw materials extraction and their processing;
- manufacturing accounts for all the process involved within MM perimeter to produce the dashboard;
- transportassess the impact attributed to all the shipments for the life cycle phases in between;
- use is based on component operation within the reference vehicle selected for a specific life time mileage;
- end of life: consists of all the process involved to recover/disposal of the materials (after vehicle dismiss) according to their typology.

Taking into account the level of maturity of the three methodologies – LCA, LCC and S-LCA – and the nature of the product under study, the system boundaries have been defined as in Figure 88 to characterize DSB panel life cycle phases for both scenarios. The two design solution differs for the: material, manufacturing and transport. The LCA and eLCC perspective are "cradle to grave" wherease, in the S-LCA a "gate to gate" perimeter has been considered and two stakeholder's groups have been included – workers and local communities. The reason for which the scope of analysis cannot be extended is the availability in the literature of social impacts data regarding use phase at component level. At the same time, the low level of experience and development of the S-LCA methodology and data could not allow evaluating the social impacts of the End-of-Life phase. One of the main open issues in the S-LCA application is the use of Functional Unit for the social assessment; in particular, there isn't a clear and common vision on how the functional unit can be used and social indicators, typically referred to the company behaviour and measured at site level, can be allocated to that. In this study, LCA and LCC results are presented as referred to the Functional Unit which is an automotive *dashboard panel*, supporting and housing all the instrumentation for the vehicle use, to be mounted on a diesel engine Alfa Romeo Mito 955, with a life-distance of 150,000 km. Concerning S-LCA this is still a challenging aspect since clear and verified way to allocate social impacts to the FU do not exist. However, also for the S-LCA an attempt is done by applying the allocation formulation proposed by the Handbook of the Roundtable for Product Social Impact Assessment. This is better described in the following paragraph regarding S-LCA.

Figure 88 – Dashboard case study system boundary.



7.8.4 LCA ANALYSIS

The present section describes the LCA analysis modalities.

7.8.4.1 LIFE CYCLE INVENTORY (LCI)

The life cycle inventory regards data collection of environmental, economic and social nature. Information has been gathered for those processes/organizations included in the system boundaries.

LCA data collection have been carried out according to the approach already applied in the previous projects: for each step the relevant energy consumption (i.e. electricity and compressed air) of the machineries, facilities equipment (i.e. lighting, air conditioning) and scraps rate have been considered. Whereas for the LCC and S-LCA this study provides the first example. More information about cost categories and social indicators are reported in the following paragraphs. In this sub-paragraph data collection to quantify relevant inputs and outputs of the phases which compose product life cycle is described. Where possible, process parameters (materials and energy flows) were obtained by direct measurements on industrial processes and/or estimation; in the others cases assumptions from GaBi 6.115 processes database have been used. In Table 71 and Table 72 a description of modalities used to collect data is reported. The materials compositions and production are grouped with the reference of Gabi datasets and data quality. The Use stage covers the operation of the FT integrated within the drivetrain system of the vehicle selected. It reflects the fuel consumption linked to the mass during the life time of a vehicle. To calculate impact imputable to the component operation over the vehicle life time [150,000 km], it was used an analytical model proposed by (Koffler and Rohde-Brandeburger 2010) considering the parameters in Table 73. The EoL management options have been modeled according to the dashboard materials composition to separate and recover/dispose plastics and elastomers from metal recovery process to the final fluff treatment in press machine [to obtain compacted fluff]. Energy consumption calculation is based on the mass of the sub-component to be treated according to the EoL options to recover/dispose certain material typology.

Table 71 – LCA data collection standard design dashboard [PP25talcum].

Standard Design			
Life cycle phase	**Specification**	**Quantity** *(per FU)*	**Process** *(GaBi; ecoinvent)*
Materials	Polypropylene [PP]	1.87 kg (6% reuse of scraps)	Polypropylene
	Talc	0.62 kg	Talcum powder
	Thermoplastic polyolefin [TPO]	1.94 kg	Polypropylene/ Ethylene Propylene Diene Elastomer Granulate (PP/EPDM, TPE-O) Mix
	Isocyanate	0.28 kg	Toluene diisocyanate
	Polyol	0.84 kg	Polyether polyol
Logistic	Total segments distance travelled	2,005 km	Truck (30-40 t gross weight; 27 t payload capacity)
Manuf.	Injection molding (1)	3.2	Electricity grid mix (IT)
	Shredding (2)	0.3	Electricity grid mix (IT)
	Plasma treatment (3)	0.19 kWh	Electricity grid mix (IT)
	Thermoforming (4)	1.41 kWh	Electricity grid mix (IT)
		0.0798Nm^3	Compressed air 7 bar (high power consumption)
	Foaming (5)	1.32 kWh	Electricity grid mix (IT)
		0.0798Nm^3	Compressed air 7 bar (high power consumption)
	Milling (6)	0.19 kWh	Electricity grid mix (IT)
	Laser processing (7)	0.18 kWh	Electricity grid mix (IT)
EoL	Laser processing (7)	0.18 kWh	Electricity grid mix (IT)
	Shredding (within drained vehicle) → landfill	2.24x10-1 kWh	Car shredder Electricity grid mix (IT); Plastic incineration (IT)
	Shredding (within drained vehicle) → incineration	2.24x10-1 kWh	Car shredder ; Electricity grid mix (IT); Plastic Landfill (IT)

Table 72 - LCA data collection standard design dashboard [PP23HGM].

	Innovative Design		
Life cycle phase	**Specification**	**Quantity** *(per FU)*	**Process** *(GaBi; ecoinvent)*
Materials	Polypropylene [PP]	1.46 kg	Polypropylene granulate
	Hollow Glass Microspheres [HGM]	0.43 kg	Silica sand; Boric acid production; Soda; Lime; Glass tube production, borosilicate
	Thermoplastic polyolefin [TPO]	1.94 kg	Polypropylene/ Ethylene Propylene Diene Elastomer Granulate (PP/EPDM, TPE-O) Mix
	Isocyanate	0.28 kg	Toluene diisocyanate
	Polyol	0.84 kg	Polyether polyol
Logistic	Total segments distance travelled	2,733	Truck (30-40 t gross weight; 27 t payload capacity)
Manuf.	Injection molding (1)	3.05	Electricity grid mix (IT)
	Plasma treatment (2)	0.29 kWh	Electricity grid mix (IT)
	Thermoforming (3)	1.41 kWh	Electricity grid mix (IT)
		0.0798Nm^3	Compressed air
	Foaming (4)	1.32 kWh	Electricity grid mix (IT)
		0.0798Nm^3	Compressed air
	Milling (5)	0.01 kWh	Electricity grid mix (IT)
	Laser processing (6)	0.21 kWh	Electricity grid mix (IT)
EoL	Shredding (within drained vehicle) → landfill	1.86x10-1 kWh	Car shredder; Electricity grid mix (IT); Plastic incineration (IT)
	Shredding (within drained vehicle) → incineration	1.86x10-1 kWh	Car shredder; Electricity grid mix (IT); Plastic Landfill (IT)

Table 73 - LCAdata collection Use phase, vehicle technical data and model parameter for dashboard.

Technical data referring to car model		
Vehicle technical characteristic	Vehicle model	Alfa Romeo Mito 1.6, Diesel (1600 cm3, 74 kW)
	Vehicle mass	1360
	Emission stage (e.g. EURO5)	EURO 5
	Motorway per-km CO_2 emission [g/km]	125
	Mixed consumption [l/100km]	8.1
Operation	Vehicle life time [km] - dm	150,000
Analytic model [NEDC]	Mass induced fuel consumption [l/100km*100kg] - FRV_PMR [Diesel] - fm	0.12
Mass [m]	Vehicle equipped with standard dashboard [kg]	4,722
	Vehicle equipped with innovative dashboard [kg]	3,926
Fuel density	Diesel [kg/dm^3]	0.84
Specific consumption [kg/kg fuel]	CO_2 emissions generated during the consumption of 1 kg of fuel [kg CO_2/Kg fuel] – f_{CO2}	3.12
	SO_2 emissions generated during the consumption of 1 kg of fuel [kg SO_2/Kg fuel] - f_{SO2}	0.00015

7.8.4.2 LCA LIFE CYCLE IMPACT ASSESSMENT (LCIA)

In this section life-cycle environmental impact has been calculated on the basis of data gathered during the inventory; it has been done by applying *Classification* and *Characterisation* to LCI data according to ISO 14040 standard guidelines. The results of Life Cycle Impact Assessment are reported below; this has been obtained according to *CML 2001 Apr. 2016*regulations, the *Primary Energy Demand (PED)* category from renewable and non-renewable resources (gross cal. value) has been considered. Results are presented in Figure 89in a form to show, for each class of environmental impact, the contribution of each life cycle stage, on the total impact, for the two design solutions, whereas the total impact percentages delta [Δ%] for each impact indicator are reported in Table 74.

Figure 89 – LCIA results dashboard project.

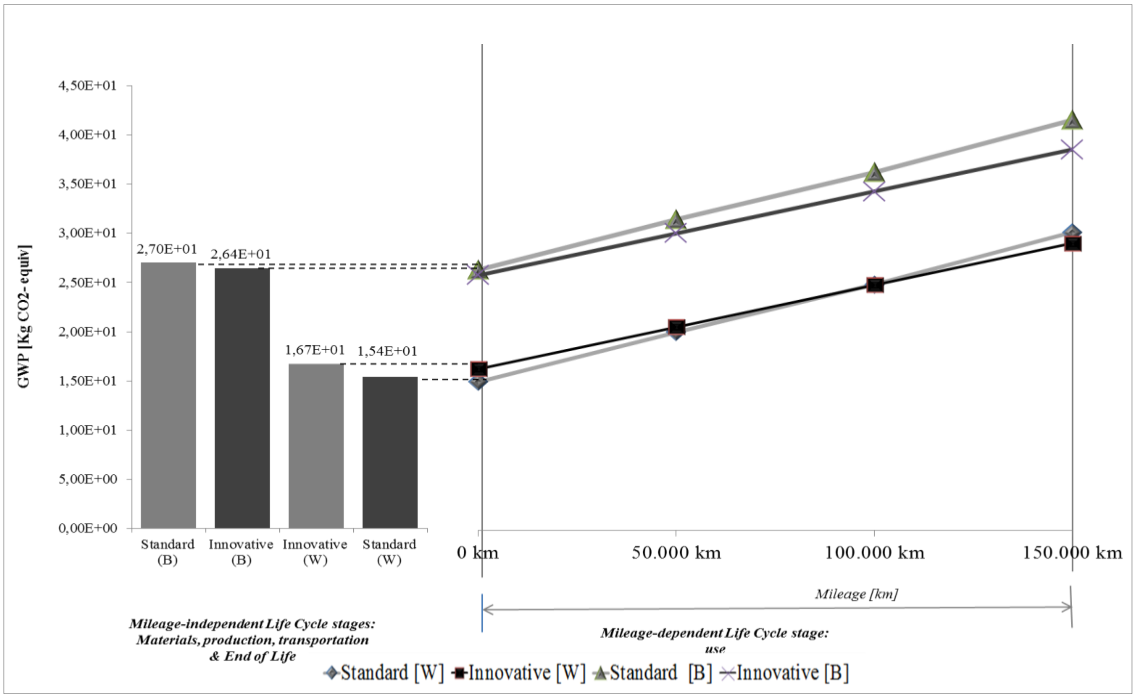
Table 74 - Dashboard total impact percentage delta decrease (-) increase ( ), worst option (W) and best option (B).

Impact categories	Δ% (W)	Δ% (B)
CML2001 - Jan. 2016, Abiotic Depletion (ADP elements) [kg Sb eq.]	53%	52%
CML2001 - Jan. 2016, Abiotic Depletion (ADP fossil) [MJ]	0%	0%
CML2001 - Jan. 2016, Acidification Potential (AP) [kg SO2 eq.]	2%	2%
CML2001 - Jan. 2016, Eutrophication Potential (EP) [kg Phosphate eq.]	-1%	0%
CML2001 - Jan. 2016, Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	-4%	-4%
CML2001 - Jan. 2016, Global Warming Potential (GWP 100 years) [kg CO2 eq.]	-4%	-8%
CML2001 - Jan. 2016, Human Toxicity Potential (HTP inf.) [kg DCB eq.]	-3%	-4%
CML2001 - Jan. 2016, Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	0%	0%
CML2001 - Jan. 2016, Ozone Layer Depletion Potential (ODP) [kg R11 eq.]	-2%	-2%
CML2001 - Jan. 2016, Photochemical. Ozone Creation Potential (POCP) [kg Ethene eq.]	-13%	-13%
CML2001 - Jan. 2016, Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	-14%	-14%
Primary energy demand from ren. and non-ren. resources (gross cal. value) [MJ]	-1%	-1%

GHG EMISSIONS BREAK-EVEN

In Figure 90 is reported the GHG emissions of CO_2 over the life cycle contribution of the standard and innovative Dashboard. The total amount is separated according to static attribution, as a sum of the dashboard life cycle occurred during the upstream and downstream activities (materials extraction and production, logistic, component manufacturing and EoL) with reference of the component operational use. Overall are presented four scenarios considering the EoL differentiation as worst option [W] considering plastic landfill and, on the contrary, the case where plastics are incinerated [B]. The separation among the LC contribution is due to the fact that, CO2 emissions are directly dependent on component use, in fact the more the vehicle runs the more emissions are generated. Different consideration could be retrieved considering the two EoL options. In the incineration case the innovative solution represent the most favorable scenario option. On the contrary considering landfill [W] the counterbalance of the emissions convenience of the innovative dashboard occurs after vehicle mileage of roughly 78,000 km (break-even point). In fact, at the beginning, the standard dashboard activities generate lower emissions than the standard.

Figure 90 – GHG emissions breakeven dashboard.



7.8.4.3 LCA INTERPRETATION

LCIA results reveal that the most two impacting LC phases for the two solutions are: materials and use, except for AP and MAETP categories (due to the expenditure of electricity and compressed air). Despite the negligible contribution of EoL and logistic, it is important to underlying the slight pejorative impact of the innovative due to the increase of the total distance travelled. From the results could be seen that the innovative solution worsen the effect on material impact: this is principally due to the use of the hollow glass microspheres but also to the fact that part of the standard compound could be reused for further processing, differently from the innovative. As lighter solution the innovative reduce the impact on use. Considering the total impact contribution the selection of the landfill and incineration option has an effect on HTP, GWP and EP categories. Considering the total impact contribution of the single indicator, the innovative design choice is favorable for the following: ADP$_{\text{element}}$ (up to 51%) and ADPelements, AP and MAETP (less than 1%). Materials impact particularly ADPelements, ODP anf HTP category. These is principally due to the use of plastic.

7.8.5 ENVIRONMENTAL LIFE CYCLE COSTING

The following paragraph describes the eLCC analysis of the dashboard case study.

7.8.5.1 LIFE CYCLE INVENTORY [LCI]

The unit costs are given in Table 75. Regarding the environmental eLCC the total cost is attributed from conventional LCC with the addition of the cost derived by the CO2 emissions generated during vehicle use and their damage cost [€/kg emissions]. The Clean Vehicles Directive 2009/33 /EC. Provide valuations of specific environmental damage cost. CO_2 emissions were already calculated from LCA analysis.

Table 75 – LCC inventory dashboard standard and innovative design solutions.

Life cycle phase	Flow (*per FU)	Unit cost	Source
Material	Standard production	€ 3,20	*Primary data*
Transports	Transports (fuel and driver) per km	1.1 €/km	*Primary data*
	Truck gross weight	35 (ton)	
	Truck payload	27 (ton)	
Manufacturing	Electricity	0.12 €/kWh (average European)	*Eurostat, 2018*
Use	Diesel	1.26 €/litre (avg European price)	*IEA, 2018*
	CO_2 emissions cost	4.00×10^{-5} €/gCO_2	*European Commission*
EoL	Electricity	0.12 €/kWh (average European)	*Eurostat, 2018*
	Plastic disposal [Worst case]	0.1 €/kg	*Primary data*
Life cycle phase	**Flow (*per FU)**	**Unit cost**	**Source**
Material	Innovative solution	€ 6,19	*Primary data*
Transports	Transports (fuel and driver) per km	1.1 €/km	*Primary data*
	Truck gross weight	35 (ton)	
	Truck payload	27 (ton)	
Manufacturing	Electricity	0.12 €/kWh (average European)	*Eurostat, 2018*
Use	Diesel	1.26 €/litre (avg European price)	*IEA, 2018*
	CO_2 emissions cost	4.00×10^{-5} €/gCO_2	*European Commission*
EoL	Electricity	0.12 €/kWh (average European)	*Eurostat, 2018*
	Plastic disposal [Worst case]	0.1 €/kg	*Primary data*

7.8.5.2 LCC IMPACT ASSESSMENT [LCIA]

In Table 76 are presented the total cost attributable to the dashboard from different perspective, internalizing the cost attributable to user during vehicle use and EoL management to recover and/or disposal the relative materials. Economic assessment results are described according to the following cost categories: materials, manufacturing, transports, use and end-of-life. 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 andthe higher expenditure necessary for its implementation.

The calculation of each contribution has been accomplished as reported below:

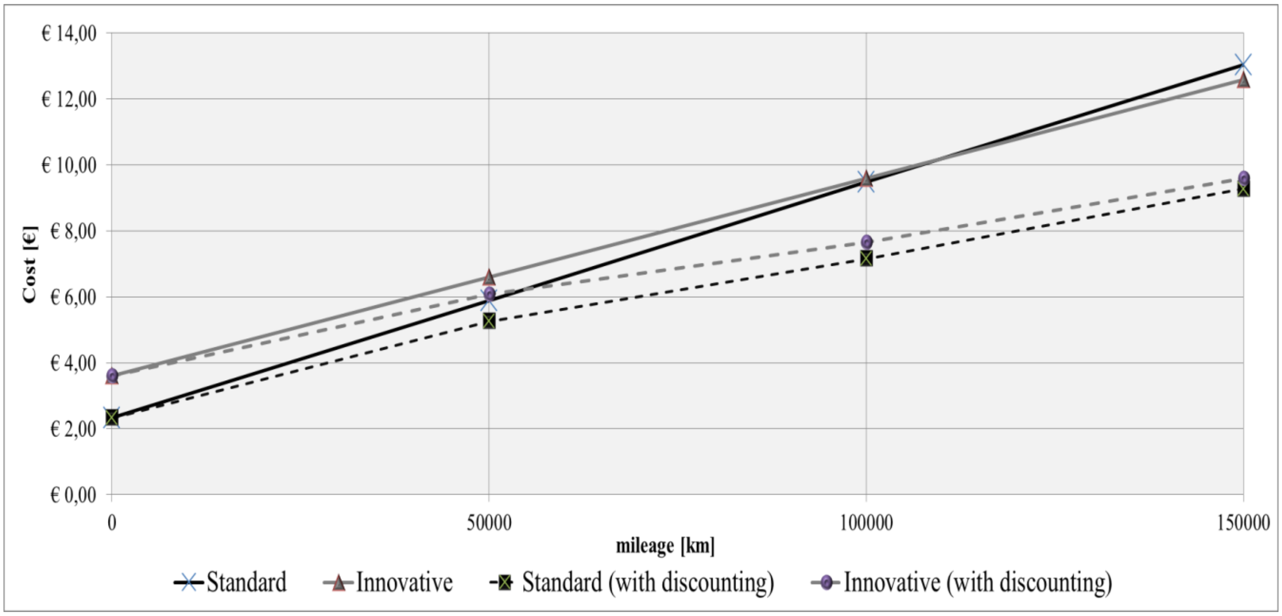
- for materials: the cost of acquisition from suppliers, with the exception of the metal part in the standard brake pedal which consider the acquisition of the metal item;
- for transport: the incidence of the cost per km multiplied by the total distance traveled and divided by truck payload capacity;
- for manufacturing: the cost attributable to each production item considering the contribution of direct labour and machine costs;
- for use: the total fuel consumption during vehicle life-time mileage of 150,000 km attributable to each component, multiplied by the average European cost of gasoline fuel;
- for EoL: the cost attributable to the disposal and/or recovery of each material flow within the dismantle line of vehicle.

Table 76 - eLCC dashboard.

Reference	Flow	Standard unit cost [€/FU]	Innovative unit cost [€/FU]
Material	Metal material	*€ 0,68*	
	Plastic material/s	*€ 0,86*	*€ 3,08*
Transport	Distance travelled	*€ 0,30*	*€ 0,09*
Manufacturing	Production	*€ 0,49*	*€ 0,43*
Total cost (MM perspective)		***€ 2,33***	***€ 3,61***
Use	Fuel (150.000 km)	*€ 10,71*	*€ 8,98*
	Externalities [CO2 emissions]	*€ 0,001*	*€ 0,001*
Total cost (user perspective)		***€ 10,71***	***€ 8,98***
EoL	Materials separation	*€ 0,03*	*€ 0,02*
	Materials recovery/dispose	*€ 0,23*	*€ 0,36*
Total life cycle cost		***€ 13,30***	***€ 12,97***

Figure 91depicts the fuel consumption cost break-even analysis over the vehicle 150,000 km mileage of use. A sensitivity analysis reporting a comparison among discounting and non-discounting calculation has been accomplished. From the line chart could be observed a cost break-even point at 100,000 km of distance travelled considering cost without discounting. Instead, if use cost are calculated with discounting method, the economic trade-off is shifted to over the 150,000 km of vehicle use.

Figure 91 – Fuel cost break-even dashboard.



7.8.5.3eLCC INTERPRETATION

From eLCC results could be concluded that material and use costs 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. Despite the innovative materials has a cost acquisition of 3 times more than the standard, the trade-off between material and use phase expenditures is in favor of the lightweight solution. Considering production expenditure the economic convenience is in favour of the new design since it is due to the reduction of time cycle and the energy expenditure (in the standard process there is an additional shredding process). Including cost acquisition, the new design solution increases production cost for the company. To sum up, considering the total amounts of cost expenditure, the less outcomes are registered for the innovative lighter dashboard.

7.8.6 SOCIAL LIFE CYLE ASSESSMENT S-LCA

The following paragraph explains the social life cycle assessment methodology applied to the dashboard.

7.8.6.1 S-LCA INVENTORY

The data inventory has been developed according to the quantitative approach, proposed in the Handbook for Product Social Impact Assessment. The data inventory includes three main steps:

- Collection;
- Allocation to FU;
- Aggregation.

Data collection regards “workers” and “local communities” groups of stakeholders (Table 77). One or two performance indicators represent each social topic. The quantitative indicators are in two forms: absolute numbers (e.g. number of actions) or percentages (e.g. % of workers).

The social topic score are dimensionless number that represents the impact of the product with regard to a social topic.

Table 77 - List of stakeholders and social topic associated included in the social assessment of dashboard.

Stakeholder Group	Social topics	Stakeholder group	Social topics
Workers	Health and safety	Workers	Training and education
	Wages		Work-life balance
	Social benefits		Job satisfaction and engagement
	Working hours	Local communities	Health and safety
	Child labour		Access to tangibleresources
	Forced labour		Local capacity building
	Discrimination		Community engagement
	Freedom of association and collective bargaining		Employment
	Employmentrelationship		

The data collection for the dashboard has involved only the manufacturing plant of Magneti Marelli 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 reported in paragraph 1.4 was used to determine the allocation factor (Table 78).

Table 78 - Data for the calculation of 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 , for the reporting period of one year (as established for LCA and eLCC data collection).

Table 79, for the reporting period of one year (as established for LCA and eLCC data collection).

Table 79- Allocated data (LCSi) of the Magneti Marelli plant involved in the dashboard production.

	Performance Indicators	Unit	Allocated Data
Workers	Number of hours of health & safety training given	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	%	0%
	Number of hours of child labour identified	Hours	0
	Number of actions during the reporting period targeting business partners to raise awareness of the issue of child labour	Actions	0
	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	%	1%
	Percentage of workers who participated in a job satisfaction and engagement survey	%	34%
	Worker turnover rate	%	8%
Local communities	Number of programs targeting capacity building in the community	Programmes	0
	Number of people in the community benefitting from capacity building programmes	Persons	0
	Number of programmes or events targeting community engagement	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

Overall, the allocated data for each life cycle stage are then aggregated in order to obtain the aggregated value of each indicator along the product life cycle (PLC indicator) (Table 80).In this case, data aggregation was done only considering the single plant of Magneti Marelli, using the same formula described in paragraph 0 and using an LCSi hours value (hours worked to produce 1 unit of the product assessed) of 0.12.

Table 80 - Aggregated values PLC of dashboard

Performance indicators	**Unit**	**PLC**
Number of hours of health and safety training per worker given	Hours	0.136
Average rate of incidents	Number	0.053
Percentage of workers whose wages meet at least legal or industry minimum standards 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	%	0%
Number of hours of child labour identified	Hours	0
Number of actions targeting business partners to raise awareness of child labour.	Actions	0
Number of hours of forced labour identified	Hours	0
Number of actions targeting business partners to raise awareness of 8forced labour.	Actions	0
Number of complaints identified during the reporting period related to discrimination.	Complaint	0
Number of actions taken to increase staff diversity and/or promote equal opportunities.	Actions	0
Percentage of workers who are members of associations able to organise themselves	%	40.17%
Percentage of workers who have documented employment conditions.	%	100%

Numbers of hours of training per employee during the reporting period.	Hours	0.128
Percentage of workers with direct family responsibilities who were eligible for maternity protection, or to take maternity, parental or compassionate leave	%	1%
Percentage of workers who participated in a job satisfaction and engagement survey	%	34%
Worker turnover rate during the reporting period.	%	8.29%
Number of programmes to enhance community health or safety.	Program	0
Number of adverse impacts on community health or safety identified	Adv. impact	0
Number of programmes to enhance community access to tangible resources or infrastructure.	Program	0
Number of adverse impacts on community access to tangible resources or infrastructure	Adv. impact	0
Number of programmes targeting capacity building in the community	Programmes	0
Number of people in the community benefitting from capacity building programmes	Persons	0
Number of programmes or events targeting community engagement	Programmes	0
Number of new jobs created	New jobs	0
Number of jobs lost	Jobs lost	0

7.8.6.2 S-LCA RESULTS

Overall results can be presented as allocated values separated for each company involved in the product life cycle or as an evaluation of LC values performances with respect to reference system.

The first allows identifying and evaluating performances of each actor involve in the supply chain/life cycle while the second is more appropriate to evaluate the general social performance of the product life cycle by comparing it to an alternative solution or to a reference situation. In this paragraph results about referencing are reported, in particular Table 81 lists the reference values provided by the Handbook and the referencing process, among the three proposed ones, for each indicator.

Table 81- 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	hours	1	worst	1
	Average rate of incidents	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	%	100%	ideal	3

	industry minimum standards and their provision fully complies with all applicable laws.				
	Percentage of workers who exceeded 48 hours of work	%	0%	ideal	2
	Number of hours of child labour identified	hours	0	ideal	2
	Number of actions targeting business partners to raise awareness of the issue of child labour	actions	1	worst	1
	Number of hours of forced labour identified	hours	0	ideal	2
	Number of actions targeting business partners to raise awareness of the issue of forced labour	actions	1	worst	1
	Number of complaints identified period related to discrimination	Compl.	0	ideal	2
	Number of actions taken to increase staff diversity and/or promote equal opportunities	actions	1	worst	1
	Percentage of workers identified 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	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	%	100%	ideal	3
	Percentage of workers who participated in a job satisfaction and engagement survey	%	100%	ideal	3
	Worker turnover rate	%	0%	ideal	2
Local communities	Number of programmes to enhance community health or safety	programmes	1	worst	1
	Number of adverse impacts on community health or safety identified	adverse impacts	0	ideal	2
	Number of programmes 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.	adverse impacts	0	ideal	2
	Number of programmes targeting capacity building in the community	programmes	1	worst	1
	Number of people in the community benefitting from capacity building programmes	persons	1	worst	1
	Number of programmes or events targeting community engagement	programmes	1	worst	1
	Number of new jobs created	new jobs	1	worst	1
	Number of jobs lost	jobs lost	0	ideal	2

The calculated performance values are listed in Table 82; 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 82 S-LCA results: performance values of the dashboard.

Performance indicators	Unit	PV	Performance evaluation
Number of hours of health and safety training per worker given during the reporting period.	Hours	-0.864	negative performance
Average rate of incidents during the reporting period.	Number	-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%	target or minimum scenario has been reached
Percentage of workers who are paid a living wage.	%	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%	target or minimum scenario has been reached
Percentage of workers who exceeded 48 hours of work per week regularly during the reporting period.	%	0%	target or minimum scenario has been reached
Number of hours of child labour identified during the reporting period.	Hours	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	-1	negative performance
Number of hours of forced labour identified during the reporting period.	Hours	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	-1	negative performance
Number of complaints identified during the reporting period related to discrimination.	Complaints	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	-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%	positive performance
Percentage of workers who have documented employment conditions.	%	100%	target or minimum scenario has been reached
Numbers of hours of training per employee during the reporting period.	Hours	-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%	positive performance
Percentage of workers who participated in a job satisfaction and engagement survey during the reporting period.	%	34%	positive performance
Worker turnover rate during the reporting period.	%	-8.29%	negative performance
Number of programmes during the reporting period to enhance community health or safety.	Programmes	-1	negative performance
Number of adverse impacts on community health or safety identified during the reporting period.	Adverse impacts	0	minimum scenario has been reached
Number of programmes during the reporting period to enhance community access to tangible resources or infrastructure.	Programmes	-1	negative performance
Number of adverse impacts on community access to tangible resources or infrastructure during the reporting period.	Adverse impacts	0	target or minimum scenario has been reached
Number of programmes targeting capacity building in the community during the reporting period.	Programmes	-1	negative performance
Number of people in the community benefitting from capacity building programmes during the reporting period.	Persons	-1	negative performance
Number of programmes or events targeting community engagement during the reporting period.	Programmes	-1	negative performance
Number of new jobs created during the reporting period.	New jobs	-1	negative performance
Number of jobs lost during the reporting period.	Jobs lost	0	target or minimum scenario has been reached

7.8.7 LCSA - INTERPRETATION

The present case study shows a first application of the LCSA comparative methodology on a Magneti Marelli component. The innovativeness that the present analysis brings is a full comparative LCSA of two different design solutions, with particular relevance on the possible adoption of an innovative material for the production of a dashboard and the consequences that lead in the variation of its life cycle from an environmental, economic and social point of view.

In this way, it was possible to obtain a complete overview of the possible advantages and disadvantages that could emerge from the adoption of the innovative design solution.

The LCSA was found an integral method based on the principles of completeness, which allow for the identification of the specific “issue aspect” for possible improvement opportunities along product life cycle and to make “comparative assessment” between different design solutions. In this way, the Product Social Impact Assessment was seen a business driver and a source of inspiration for product innovation and furthermore a proper instrument to identify possible social hotspots within the company perimeter or along the product life cycle.

The data collection, developed according to the proposed social indicators, was found feasible within the perimeter of the Magneti Marelli plant of San Benigno Canavese (IT) and lead to a more sensible view (for the company employee) of the possible social implications regarding the manufacturing. In this sense, interesting results could come from the integration with approaches and indicators already used by the company within the organizational strategies for sustainability (e.g. GRI indices).For instance regarding the social assessment, different from other social analysis (ISO 26000, Social Footprint (SPF) ect.) which provides results at organization level, the Social Life Cycle Assessment results are expressed at product level and in a quantitative way, thus providing useful insights to make comparative assessment between different solutions. However, a clear and robust interpretation of social results is still not possible due to the social assessment level of maturity. Further methodology advancements are expected in the near future, therefore future project could be beneficial to test and follow methodology progress.

Outcomes interpretation in terms of component sustainability was still found a challenging issues and this can be ascribed to two main reasons. The first is the level of maturity of the methodology, especially regarding the social assessment; the second is the nature of the project, which was not based on a comparison but only on an absolute assessment of the current component design. The third reason is the need of a methodology able to integrate the “economic”, “social” and “environmental” results under a single point. Such considerations could provide the starting points for further projects.

8. SECOND STRATEGY: LAYOUT OPTIMIZATION

In chapter 8 are discussed with major details each steps of the analysis for each component regarding layout optimization strategy application. The structure is presented according to the ISO 14040 for LCA and eLCC respectively. To start, a brief description of the "goal and scope" of the study is presented, providing an explanation of component functionality and location within vehicle system. The following studies regard the assessment of a current component design (named standard) with a novel proposal (named innovative). Therefore, the main results regard the methodology applicability in terms of data availability, indicators relevance and appropriateness, and results presentation and interpretation are presented. Outcomes in terms of component sustainability could be retrieved only concerning environmental and economic assessment; however, more insights could be obtained in a comparative analysis.

8.1 MUFFLER PROJECT

This project focuses on the environmental impact assessment analysis between *two different production technologies* for a specific automotive component: a muffler. The method adopted is a combination of a ***Life Cycle Assessment (LCA)*** and a ***Life Cycle Costing (LCC)*** as a part of Life Cycle Sustainability Assessment (LCSA) analysis. The purpose is to make evidence on which of the two production technologies cause the most environmental impact and economic expenditure, considering the full product life cycle. For this purpose, the perimeter of the analysis include all the phases upstream and downstream of the MM production stage, performing in this way what is so called "cradle to grave" approach analysis. Overall, the main goals of the project are:

- verify applicability of LCA and LCC as a supporting tool to "identify the main sustainability hotspots in the product life cycle - especially regarding its technology function during its operation on the vehicle - therefore guide strategy development" and provide elements for production decisions for muffler production;
- develop data collection on environmental and economic impact of the different production technologies regarding the manufacturing of a muffler;
- create a model for the environmental assessment of a specific technology;
- provide guidance on different product design proposals based on environmental and economic impact point of view.

8.1.1 GOAL AND SCOPE

The overall scope of the study is to quantify the environmental and economic impacts of the entire central muffler life cycle, comparing a rolled muffler with a stamped one, both made with the same materials. The main driver taken into account for improvement is the technology variation which leads to a *simplification of the manufacturing chain*, with a *shortening of the total time cycle* and of *the total energy expenditure* for the production. The present analysis can be used to supply sustainability information to improve product performances in terms of:

- life cycle perspective to assess a balance among environment and economic point of view, two different manufacturing technologies for the production of a specific component to apply at macro-level;
- find insight in the specific context of manufacturing plant;
- quantifying energy and resource intensive processes and minimizing their impact.

In order to assess the environmental and economic impact of the innovative production technology to be implemented for the manufacturing of a muffler, a comparative LCA and eLCC between the two different design solutions has been accomplished. The main technical difference data of the two design solutions are reported in Table 83. The consequences of production technology variation (listed in Table 83) are: i) the change of the production technology and ii) the sub-components' weight and geometry variation.

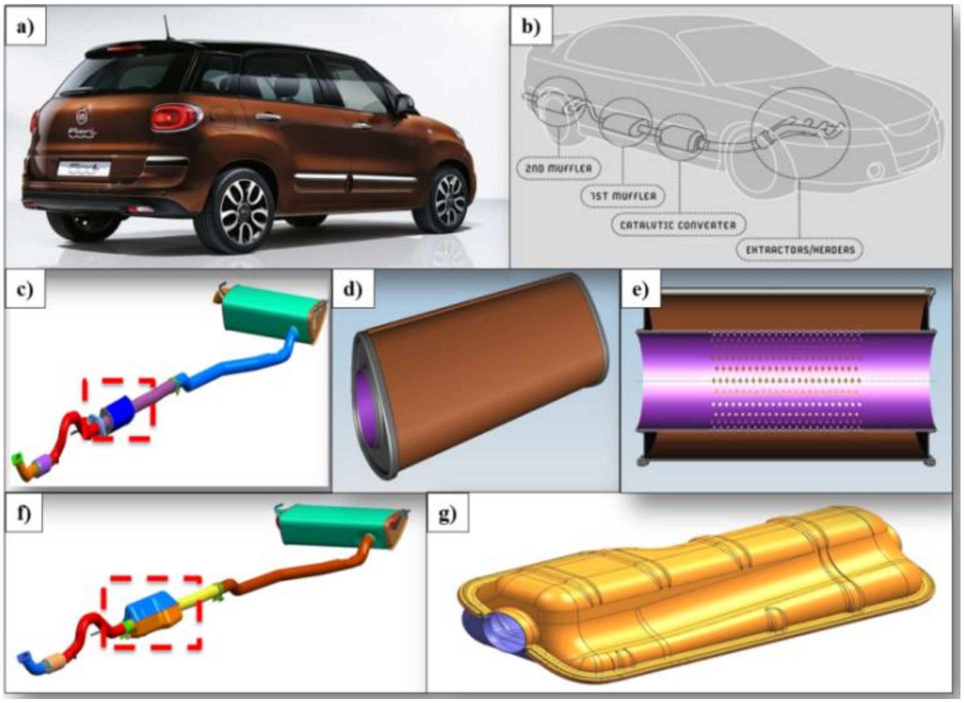
Table 83 - Technical data of muffler design solutions.

Features	Standard	Innovative	Variation
Weight (kg)	3.611	3.531	2% weight reduction
Technology	Rolled	Shells stamped and welding	Technology
Part/s	1. Pipe (Stainless steel AISI 441)	1. Pipe (Stainless steel AISI 441)	Weight
	2. Envelope (Stainless steel AISI 441)	2. Shells (Stainless steel AISI 441)	Geometry and weigh
	3. Endcap (Stainless steel AISI 441)	3. Baffle (Stainless steel AISI 441)	Geometry and weigh
	4. Absorption Material [(Glass fibers (GF)]	4. Absorption material [Glass fibers (GF)]	Weight
Production technology	Cutting → Lock seaming → Rolling → Envelope sheet stamping → Welding	Upper and lower shell stamping → Lock seaming → Crimping headframe → Welding	Production technology and time cycle

8.1.2 COMPONENT DESCRIPTION

The muffler is engineered component, which takes part in the exhaust system of a vehicle, whose main function is the acoustic soundproofing to reduce the noise of the sound pressure generated by the engine. The central muffler of complete exhaust systems can be rolled or stamped. In both cases, glass fiber is used as internal sound protection: the difference between the two solutions is given by the technology to make the envelope. In the first case, the envelope is rolled around the glass fiber while in the second case two stamped shells are welded or locked together. The following Figure 92 shows up a complete scheme of the components.

Figure 92 – a) Reference vehicle, b) location of the muffler within vehicle system, c) standard exhaust system, d) standard muffler design, e) section of standard muffler design, f) innovative exhaust system, g) innovative muffler design.



8.1.3 SYSTEM BOUNDARIES AND FUNCTIONAL UNIT

In this paragraph, the product system and the system boundaries are described. Regarding the system boundary, LCA and LCC are conducted by defining product systems as models that describe the key elements of physical systems. The system boundary defines the unit processes to be included in the system. Ideally, the product system is modelled in such a manner that inputs and outputs at its boundary are elementary flows. The choice of the elements of the physical system to be modelled depends on the goal and scope definition of the study. The two muffler design options are analyzed as integrated within the exhaust system through all its life cycle, according to a “cradle to gate” approach, splitting it in the following macro-phases: materials, manufacturing, use, end of life and transport of each phase in between. For the present case study are considered the life cycle phase grouped according to:

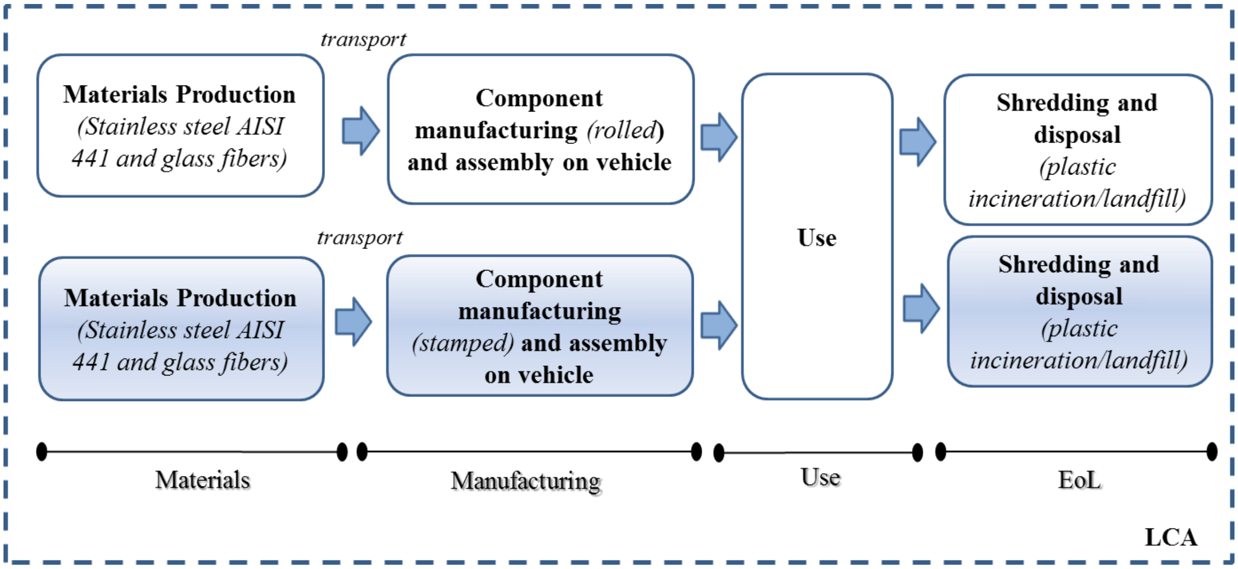
- materials which includes raw materials extraction and their processing;
- manufacturing accounts for all the process involved within MM perimeter to produce the muffler;
- transport assess the impact attributed to all the shipments for the life cycle phases in between;
- use is based on component operation within the reference vehicle selected for a specific life time mileage;
- end of life: consists of all the process involved to recover/disposal of the materials (after vehicle dismiss) according to their typology.

Following

Figure 93characterizes muffler module life cycle phases for both scenarios.

The two design solution differs for the: material, manufacturing and transport. The Functional Unit (FU) of the present analysis is one *automotive muffler* integrated within exhaust system, supporting and housing all the instrumentation for vehicle use, to be mounted a 2,4l FIAT 500 L, gasoline car for 150,000km on 10 years.

Figure 93 - Muffler case study system boundary.



8.1.4LCA ANALYSIS

Here is presented the LCA methodology application on muffler design solutions.

8.1.4.1 LIFE CYCLE INVENTORY (LCI)

In this sub-paragraph, data collection to quantify relevant inputs and outputs of the phases, which compose product life cycle, is described. Where possible process parameters (materials and energy flows) were obtained by direct measurements on industrial processes and/or estimation; in the others cases, assumptions from GaBi 6.115 processes database have been used. In Table 84 and Table 85 a description of modalities used to collect data is reported. The materials compositions and production are grouped with the reference of Gabi datasets and data quality. The Use stage covers the operation of the muffler integrated within the exhaust system of the vehicle selected. It reflects the fuel consumption linked to the mass during the life time of a vehicle.

To calculate impact imputable to the component operation over the vehicle life time [150,000 km], it was used an analytical model proposed by (Koffler and Rohde-Brandeburger 2010) considering the parameters in Table 86. The EoL management options have been modeled according to the muffler materials composition to separate:

- Ferrous materials (steel) : metal recovery process → screening → magnetic separation → eddy current → inductive resonance → ballistic separation [to separate aluminium];
- Plastics, elastomers, and electronics (glass fibers): from metal recovery process → fluff treatment in press machine [to obtain compacted fluff].

Energy consumption calculation is based on the mass of the sub-component to be treated according to the EoL options to recover/dispose certain material typology. Materials have been classified according to: metals for steel content materials and others for glass fibers content. The End of Life modelling includes the environmental burdens of recycling processes and grants credits for the recycled/ recovered materials.

Table 84 - LCI standard design solution [rolled manufacturing technology].

	Standard Design		
Life cycle phase	**Specification**	**Quantity** *(per FU)*	**Process** *(GaBi; ecoinvent)*
Materials	1. Pipe [Stainless steel (AISI 441)]	2.201 kg	Steel welded pipe (worldsteel)
	2. Envelope [Stainless steel (AISI 441)]	0.87	Stainless steel cold rolled coil (430)
	3. Endcap [Stainless steel (AISI 441)]	0.22 kg	Stainless steel cold rolled coil (430)
	4. Absorption material [Glass fibers (GF)]	0.19 kg	Glass wool [Minerals]
	Steel-auxiliary material for welding process	0.131 kg	Steel wire rod
Logistic	Total segments distance travelled	885 km	Truck-trailer, Euro 4, 34 - 40t gross weight / 27t payload capacity
Manufacturing	1.Cutting	4.8x10-2 kWh	Electricity grid mix (IT)
	2. Lock seaming	9.52x10-2 kWh	Electricity grid mix (IT)
	3. Rolling	7.13x10-2 kWh	Electricity grid mix (IT)
	4. Envelope sheet stamping	9.83x10-2 kWh	Electricity grid mix (IT)
	5. Welding	7.1x10-2 kWh	Electricity grid mix (IT)
EoL	1) Shredding (within drained vehicle) → Materials separation → Metals recovery and plastic landfill	0.077 kWh	Car shredder; Steel mill scales - scrap credit (open loop); Steel rebar (23%); Electricity grid mix (IT); EU-28: Plastic waste on landfill; Electricity
	2) Shredding (within drained vehicle) → Materials separation → Metals recovery and plastic incineration	0.077 kWh	Car shredder; Steel mill scales - scrap credit (open loop); Steel rebar (23%); Electricity grid mix (IT); U-28: Polyamide (PA) 6 GF30 in waste incineration plant; Electricity grid mix

Table 85 - LCI standard design solution [stamped manufacturing technology].

	Innovative Design		
Life cycle phase	**Specification**	**Quantity** *(per FU)*	**Process** *(GaBi; ecoinvent)*
Materials	1. Shells [Stainless steel (AISI 441)]	2.35 kg	Stainless steel cold rolled coil (430)
	2. Pipe [Stainless steel (AISI 441)]	0.65 kg	Steel welded pipe (worldsteel)
	3. Baffle [Stainless steel (AISI 441)]	0.26 kg	Stainless steel cold rolled coil (430)
	4. Absorption material [Glass fibers (GF)]	0.14 kg	Glass wool [Minerals]
	Steel-auxiliary material for welding process	0.131 kg	Steel wire rod
Logistic	Total segments distance travelled	877 km	Truck-trailer, Euro 4, 34 - 40t gross weight / 27t payload capacity
Manufacturing	1. Upper and lower shell stamping	7.86x10-2 kWh	Electricity grid mix (IT) (Gabi)
	2. Lock seaming	9.52x10-2 kWh	Electricity grid mix (IT)
	3. Crimping headframe	6.22x10-2 kWh	Electricity grid mix (IT)
	4. Welding	7.13x10-2 kWh	Electricity grid mix (IT)
EoL	1) Shredding (within drained vehicle) → Materials separation → Metals recovery and plastic landfill	0.137 kWh	Car shredder; Steel mill scales - scrap credit (open loop); Steel rebar (23%); Electricity grid mix (IT); EU-28: Plastic waste on landfill; Electricity grid mix (IT)
	2) Shredding (within drained vehicle) → Materials separation → Metals recovery and plastic incineration	0.137 kWh	Car shredder; Steel mill scales - scrap credit (open loop); Steel rebar (23%); Electricity grid mix (IT); U-28: Polyamide (PA) 6 GF30 in waste incineration plant; Electricity grid mix

Table 86 - LCI Use phase, vehicle technical data and model parameter for muffler.

Technical data referring to car model equipped with the muffler		
Vehicle technical characteristic	Vehicle model	2,4l gasoline
	Vehicle mass	1390
	Emission stage (e.g. EURO5)	5
	Motorway per-km CO_2 emission [g/km]	161
	Mixed consumption [l/100km]	7.4
Operation	Vehicle life time [km] - dm	150,000
Analytic model [NEDC]	Mass induced fuel consumption [l/100km*100kg] - FRV_PMR [Gasoline] - fm	0.15
Mass [m]	Vehicle equipped with standard muffler [kg]	3.611
	Vehicle equipped with first innovative muffler [kg]	3.531
Fuel density	Gasoline [kg/dm³]	0.74
Specific consumption [kg/kg fuel]	CO_2 emissions generated during the consumption of 1 kg of fuel [kg CO_2/Kg fuel] – f_{CO2}	3.12
	SO_2 emissions generated during the consumption of 1 kg of fuel [kg SO_2/Kg fuel] - f_{SO2}	0.00015

In the modeling of auxiliary module's life cycle, the packaging consumption have been excluded since materials are always recovered for the same purposes.

8.1.4.2 LCA LIFE CYCLE IMPACT ASSESSMENT (LCIA)

In this section life-cycle environmental impact has been calculated on the basis of data gathered during the inventory; it has been done by applying *Classification* and *Characterisation* to LCI data according to ISO 14040 standard guidelines. The results of Life Cycle Impact Assessment are reported below; this has been obtained according to *CML 2001 Apr. 2016*regulations, the *Primary Energy Demand (PED)* category from renewable and non-renewable resources (gross cal. Value). Results are presented in Figure 94 in a form to show, for each class of environmental impact, the contribution of each life cycle stage, on the total impact, for the two design solutions, whereas the total impact percentages delta [Δ%] for each impact indicator are reported in Table 87.

Figure 94 – LCIA Results muffler project.

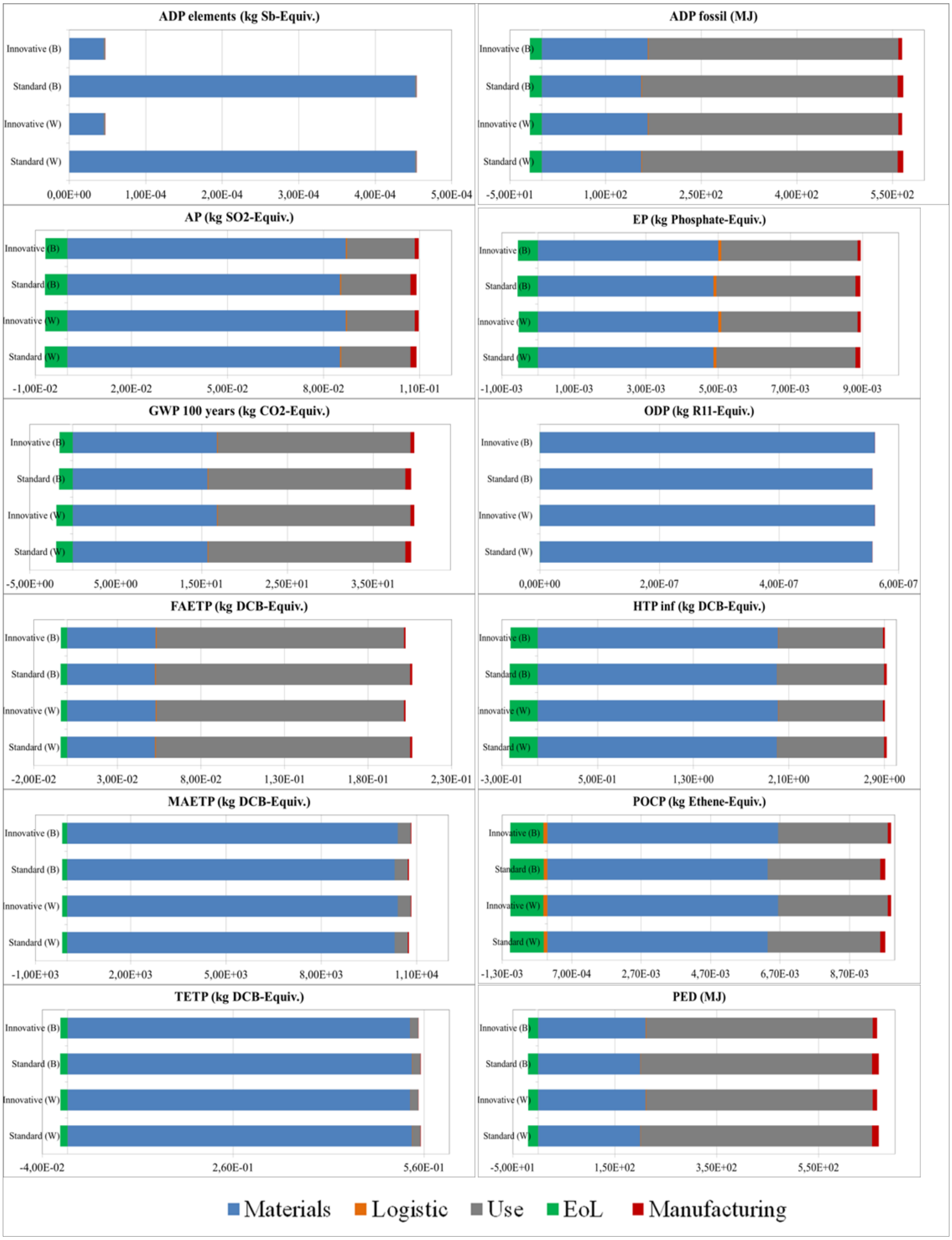


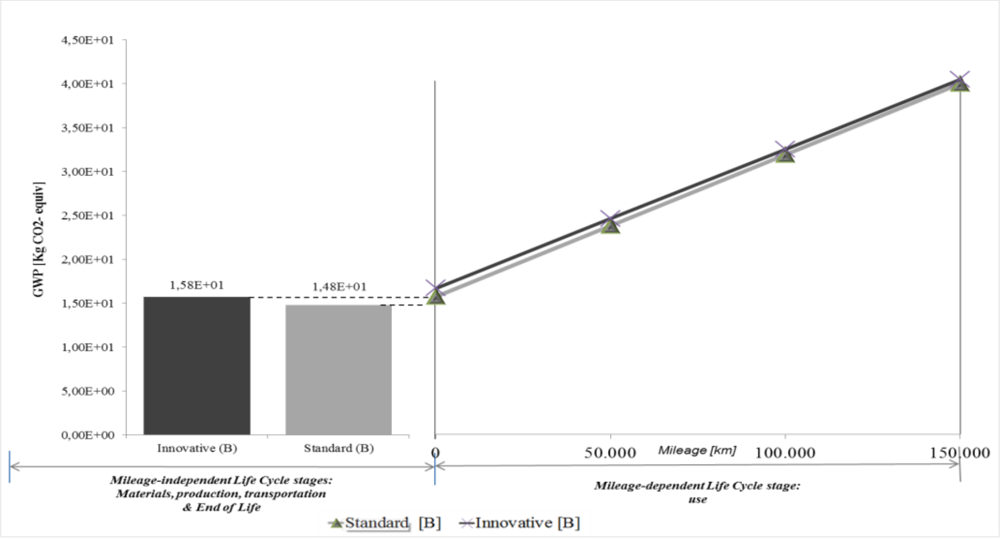
Table 87– Muffler total impact percentage delta decrease (-) increase ( ), worst option (W) and best option (B).

Impact categories	Δ% (W)	Δ% (B)
CML2001 - Jan. 2016, Abiotic Depletion (ADP elements) [kg Sb eq.]	-867%	-866%
CML2001 - Jan. 2016, Abiotic Depletion (ADP fossil) [MJ]	0%	0%
CML2001 - Jan. 2016, Acidification Potential (AP) [kg SO2 eq.]	1%	1%
CML2001 - Jan. 2016, Eutrophication Potential (EP) [kg Phosphate eq.]	0%	0%
CML2001 - Jan. 2016, Freshwater Aquatic Ecotoxicity Pot. (FAETP) [kg DCB eq.]	-2%	-2%
CML2001 - Jan. 2016, Global Warming Potential (GWP 100) [kg CO2 eq.]	1%	1%
CML2001 - Jan. 2016, Human Toxicity Potential (HTP inf.) [kg DCB eq.]	0%	0%
CML2001 - Jan. 2016, Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	1%	1%
CML2001 - Jan. 2016, Ozone Layer Depletion Potential (ODP) [kg R11 eq.]	1%	1%
CML2001 - Jan. 2016, Photochemical. Ozone Creation Potential (POCP) [kg Ethene eq.]	2%	2%
CML2001 - Jan. 2016, Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	-1%	-1%
Primary energy demand from ren. and non-ren. resources (gross cal. value) [MJ]	0%	0%

GHG EMISSIONS BREAK-EVEN

In Figure 95 is reported the GHG emissions of CO2 over the life cycle contribution of the standard and innovative auxiliary module. The total amount is separated according to static attribution, accounted for the upstream and downstream activities, with reference of the component operational use. The standard component accounts for 10 kg emissions of CO2 lower than the standard without considering component operation. On the contrary the innovative solution has a lower impact during its operation, reaching a trade-off at 149,000 km of vehicle mileage.

Figure 95 – GHG emission muffler project best scenario [incineration scenario].



8.1.4.3 LCA INTERPRETATION

In this final section the results obtained and previously shown for each process separately are now compared and interpreted. The final result of this analysis shows very similar environmental impacts for the two mufflers, since in both cases the environmental impacts are mainly due to the raw material extraction andto the use phase. Manufacturing and transport phases have very low impact compared to the other phase, with the innovative design accounting for less impact than standard. No sensible variations are perceived between the standard and innovative with the exception of ADPelements. In short, the slight decrease of metal employment did not lead to a considerable impact reduction as the lowering of component weight. Similar conclusion could be referred to the manufacturing step, since the decrease is marginally perceived.

8.1.5 ENVIRONMENTAL LIFE CYCLE COSTING

The following section describes the eLCC analysis of the muffler case study.

8.1.5.1 LIFE CYCLE INVENTORY [LCI]

The unit costs are given in Table 88 and according to what described in CHAPTER 5 (paragraph 5.1.2 *LCC methodology in Magneti Marelli*). Regarding the environmental eLCC the total cost is attributed from conventional LCC with the addition of the cost derived by the CO2 emissions generated during component LC (accounting materials, manufacturing, logistic, EoL and use over 150,000 kilometers of use) and their damage cost [€/kg emissions]. Valuations of specific environmental damage cost are provided by the Clean Vehicles Directive 2009/33/EC. CO_2 emissions were already calculated from LCA analysis.

Table 88 – LCC inventory muffler standard and innovative design solutions.

Standard muffler			
Life cycle phase	**Flow (*per FU)**	**Unit cost**	**Source**
Transports	Transports (fuel and driver) per km	1.1 €/km	*Primary data*
	Item quantity (standard material)	3.611 kg	
	Truck gross weight (ton)	37	
	Truck payload (ton)	27	
Manufacturing	Electricity (cost)	0.12 €/kWh (average European)	*Eurostat, 2018*
	Investment	1350 k€	*Primary data*
Use	Gasoline	1.46 €/litre (avg European price)	*IEA, 2018*

	CO$_2$ emissions cost	4.00×10^{-5} €/gCO$_2$	*European Commission*
EoL	Electricity (price)	0.12 €/kWh (average European)	*Eurostat, 2018*
	Plastic disposal [Worst case]	0.1 €/kg	*Primary data*
	Electricity for plastic separation	0,047 [Kwh/1kg plastic]	
	Electricity consumed for metal separation	0,04 [Kwh/1kg metal]	
	Metals recovery	0.19 €/kg	
Innovative muffler			
Life cycle phase	**Flow (*per FU)**	**Unit cost**	**Source**
Transports	Transports (fuel and driver) per km	1.1 €/km	*Primary data*
	Item quantity (innovative)	3.531 kg	
	Truck gross weight (ton)	37	
	Truck payload (ton)	27	
Manufacturing	Electricity (cost)	0.12 €/kWh (average European)	*Eurostat, 2018*
	Investment	1910 k€	*Primary data*
Use	Gasoline	1.46 €/litre (avg European price)	*IEA, 2018*
	CO$_2$ emissions cost	4.00×10^{-5} €/gCO$_2$	*European Commission*
EoL	Electricity (price)	0.12 €/kWh (average European)	*Eurostat, 2018*
	Plastic disposal [Worst case]	0.1 €/kg	*Primary data*
	Electricity for plastic separation	0,047 [Kwh/1kg plastic]	
	Electricity consumed for metal separation	0,04 [Kwh/1kg metal]	
	Metals recovery	0.19 €/kg	

8.1.5.2 LCC IMPACT ASSESSMENT [LCIA]

In Table 89 are presented the total cost attributable to the headlamp reflector from different perspective, internalizing the cost attributable to user during vehicle use and EoL management to recover and/or disposal the relative materials. Economic assessment results are described according to the following cost categories: manufacturing, transports, use and end-of-life. 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 calculation of each contribution has been accomplished as reported below:

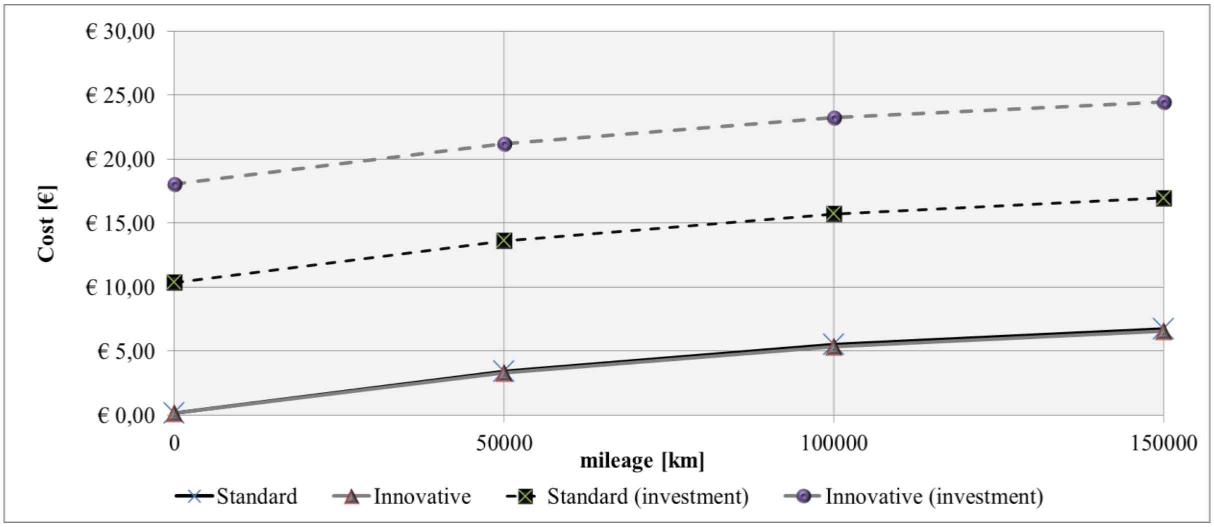
- for transport: the incidence of the cost per km multiplied by the total distance traveled and divided by truck payload capacity;
- for manufacturing: the cost attributable to each production item considering the contribution of investment for machine installation and energy costs;
- for use: the total fuel consumption during vehicle life-time mileage of 150,000 km attributable to each component, multiplied by the average European cost of gasoline fuel;
- for EoL: the cost attributable to the disposal and/or recovery of each material flow within the dismantle line of vehicle.

Table 89 - eLCC results muffler.

Reference	**Flow**	**Standard unit cost [€/FU]**	**Innovative unit cost [€/FU]**
Transport	Distance travelled	*€ 0,10*	*€ 0,09*
Manufacturing	Investment	€ 10,22	€ 17,90
	Production	€ 0,046	€ 0,036
Total cost (MM perspective)		***€ 10,36***	***€ 18,03***
Use	Fuel (150.000 km)	€ 16,943	€ 24,467
	Externalities	*€ 0,0015*	*€ 0,0015*
Total cost (user perspective)		***€ 16,94***	***€ 24,47***
EoL	Materials separation	*€ 0,15*	*€ 0,14*
	Materials recovery/dispose	-€ 0,635	*-€ 0,625*
Total life cycle cost (with investment)		***€ 26,82***	***€ 42,01***
Total life cycle cost (without investment)		***€ 6,3824***	***€ 6,2067***

Figure 96depicts the fuel consumption cost break-even analysis over the vehicle 150,000 km mileage of use. A sensitivity analysis reporting a comparison among discounting calculation accounting assuming two different scenarios, whether are considered or not the investment costs. From the line chart could not be observed that considering investment cost, the innovative solution has a high cost gap, which is not balanced with a marginal fuel saving. Instead without internalizing investment costs the innovative solution has a lower cost impact due to the energy and logistic savings.

Figure 96 – Fuel cost break-even muffler.



8.1.5.3 eLCC INTERPRETATION

Environmental LCC results are presented in such a way to distinguish each life cycle cost flow attributable to the specific item. Certainly the most discrepancy is attributed to the investment cost allocated. The new manufacturing line has revealed to be more environmentally friendly and more economic convenient if investment costs are excluded. Further perceived advantages are related to the production expenditure savings. Different consideration could be retrieved considering the different actors perspective. From MM perspective the implementation of the innovative solution means for sure a production cost decrease, without considering the investment. Benefits are identified from user perspective, considering a cost decrease of fuel consumption which increases proportioned to the mileage traveled. Moreover from EoL management point of view, the less materials are processed in the EoL; the lower cost incomes are generated.

8.2 FUEL TANK PROJECT

This project focuses on the environmental impact assessment analysis between *two different production technologies* for a specific automotive component: a fuel tank (hereafter FT). The method adopted is a combination of a ***Life Cycle Assessment (LCA)*** and a ***Life Cycle Costing (LCC)*** as a part of Life Cycle Sustainability Assessment (LCSA) analysis.

The purpose is to make evidence on which of the two production technologies cause the most environmental impact and economic expenditure, considering the full product life cycle. For this purpose, the perimeter of the analysis include all the phases upstream and downstream of the MM production stage, performing in this way what is so called “cradle to grave” approach analysis.
Overall, the main goals of the project are:

- verify applicability of LCA and LCC as a supporting tool to “identify the main sustainability hotspots in the product life cycle - especially regarding its technology function during its operation on the vehicle - therefore guide strategy development” and provide elements for production decisions for FT production;
- develop data collection on environmental and economic impact of the different production technologies regarding the manufacturing of a FT;
- create a model for the environmental assessment of a specific technology;
- provide guidance on different product design proposals based on environmental and economic impact point of view.

8.2.1 GOAL AND SCOPE

The overall scope of the study is to quantify the environmental and economic impacts of the entire FT life cycle, comparing a blowmolded fuel tank with a stamped and welded one, having different materials layer distribution. The main driver taken into account for improvement is the technology variation which leads to a *reduction of component weight* as well as for toxic materials layer thickness.
The present analysis can be used to supply sustainability information to improve product performances in terms of:

- life cycle perspective to assess a balance among environment and economic point of view, two different manufacturing technologies for the production of a specific component to apply at macro-level;
- find insight in the specific context of manufacturing plant;
- quantifying energy and resource intensive processes and minimizing their impact.

In order to assess the environmental and economic impact of the innovative production technology to be implemented for the manufacturing of a FT, a comparative LCA and eLCC between the two different design solutions has been accomplished. The main technical difference data of the two design solutions are reported in Table 90. The consequences of production technology variation (listed in Table 90) are: i) the change of the production technology and ii) the sub-components layer' weight, composition, distribution and thickness.

Table 90 – Technical data of fuel tank design solution.

Features	Standard	Innovative	Variation
Weight (kg)	7	4.715	33% weight reduction
Technology	Blowmolding	Shells injection and welding	Production technology
Part/s	1. High-density polyethylene [HDPE] layer	1. High-density polyethylene [HDPE] layer	Weight and geometry
	2. Ethylene vinyl alcohol [EVOH] layer	2. Ethylene vinyl alcohol [EVOH] layer	Weight
	3. Adhesive Resin Tie-layer [ADMER] layer	3. Adhesive Resin Tie-layer [ADMER] layer	Weight
Production technology	Blowmolding→ Post cooling → Welding (hot blade)	Injection →Welding (laser)	Production technology and time cycle diminution (13%)

8.2.2 COMPONENT DESCRIPTION

The vehicle fuel tank, as the denomination itself suggests, is a multi-layer chamber container for the fuel that takes part in the *drivetrain system*. The standard component is produced with the blowmolding technology, therefore with one single step operation. In the innovative design option, the fuel tank is obtained in two stages: firstly are produced two multilayer shells obtained by injection molding and then they are welded (

Figure 97). The new *injection molding* technology means components/functions integration, high thickness control (fuels permeation and weight reduction). Two shells welding after injection molding allows a layout optimization in order to reduce the potential leakage points. The production process of the 2 shells is based on the over-molding injection technology, realized on a unique injection machine equipped with 2 injection units and a rotary table, usable for the production of 2 parts ("2K"). The injection cycle begins with a first step of molding the inner layer of the component at the first side on the machine. After rotation of the mold, the second component is over molded on the first one, at the other side of the machine. This process allows a cycle time reduction, a lean process (2 shots on the same machine), a better balance of the injection pressure and a good adhesion between the 2 layers. The above process is considered innovative if compared with a traditional blowmolding process that is based on extrusion, a specific transformation starting from a vertical extrusion of a parison (a multilayer tube of melted polymers). The parison goes down between the two shells of a mold. Mold is being closed and gas injected into it. The plastic material, due to the pressure, is projected on the surface of the mold to take its complex form. At the end of the process, the mold opens and tank shell comes out. The excess material is cut and regrinds to be reused in the extrusion process.

Figure 97 – a) reference vehicle equipped with the fuel tank, b) upper and lower shells injected [innovative manufacturing], c) blowmolded fuel tank [standard manufacturing].

8.2.2 SYSTEM BOUNDARIES AND FUNCTIONAL UNIT

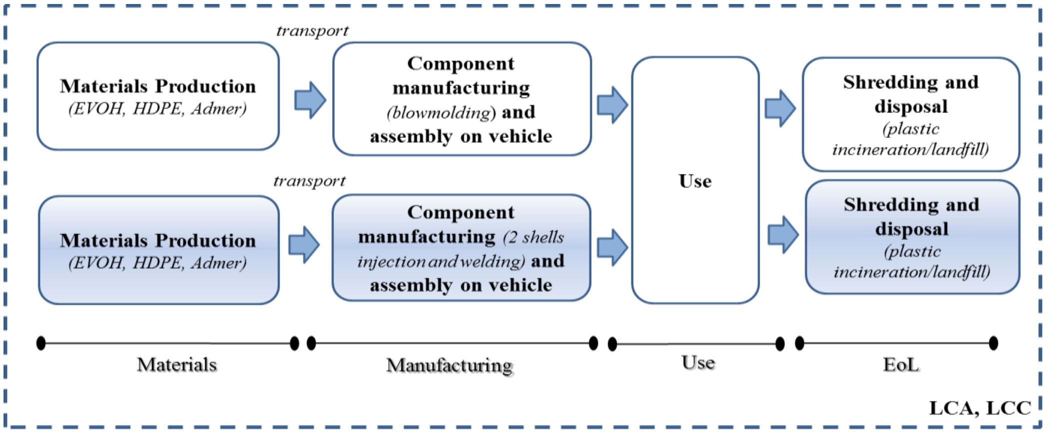
In this paragraph the product system and the system boundaries are described. Regarding the system boundary, LCA and LCC are conducted by defining product systems as models that describe the key elements of physical systems. The system boundary defines the unit processes to be included in the system. Ideally, the product system is modelled in such a manner that inputs and outputs at its boundary are elementary flows. The choice of the elements of the physical system modelled depends on the goal and scope definition of the study. The two FT are analyzed as integrated within the drivetrain system through all its life cycle, according to a "cradle to gate" approach, splitting it in the following macro-phases: materials, manufacturing, use, end of life and transport of each phase in between. For the present case study are considered the life cycle phase grouped according to:

- materials which includes raw materials extraction and their processing;
- manufacturing accounts for all the process involved within MM perimeter to produce the muffler;
- transport assess the impact attributed to all the shipments for the life cycle phases in between;
- use is based on component operation within the reference vehicle selected for a specific life time mileage;
- end of life: consists of all the process involved to recover/disposal of the materials (after vehicle dismiss) according to their typology.

Following Figure 98characterizes auxiliary module life cycle phases for both scenarios. The two design solution differs for the “material, manufacturing and transport of these two phases in between”.

The Functional Unit (FU) of the present analysis is an automotive fuel tank integrated within driven system, containing 2,4 litres of fuel to be mounted on a Fiat 500X gasoline car for a life time mileage of 150,000 km.

Figure 98 – Fuel tank case study system boundary.



8.2.4 LCA ANALYSIS

In the next paragraphs is described the LCA analysis of the fuel tank project.

8.2.4.1 LIFE CYCLE INVENTORY (LCI)

In this sub-paragraph data collection to quantify relevant inputs and outputs of the phases which compose product life cycle is described. Where possible, process parameters (materials and energy flows) were obtained by direct measurements on industrial processes and/or estimation; in the others cases assumptions from GaBi 6.115 processes database have been used. In Table 91 and Table 92 a description of modalities used to collect data is reported. The materials compositions and production are grouped with the reference of Gabi datasets and data quality. The Use stage covers the operation of the

FT integrated within the drivetrain system of the vehicle selected. It reflects the fuel consumption linked to the mass during the life time of a vehicle. To calculate impact imputable to the component operation over the vehicle life time [150,000 km], it was used an analytical model proposed by (Koffler and Rohde-Brandeburger 2010) considering the parameters in Table 93. The EoL management options have been modeled according to the fuel tank material composition to separate:plastics, elastomers, and electronics: from metal recovery process → fluff treatment in press machine [to obtain compacted fluff]. Energy consumption calculation is based on the mass of the sub-component to be treated according to the EoL options to recover/dispose certain material typology. The End of Life modelling includes the environmental burdens of recycling processes and grants credits for the recycled/ recovered plastic materials.

Table 91 - LCI standard design solution [Blowmolding production technology].

	Standard Design		
Life cycle phase	**Specification**	**Quantity** *(per FU)*	**Process** *(GaBi; ecoinvent)*
Materials	1. High-density polyethylene [HDPE] layer	6.245 kg (2.17 regrind)	HDPE (Polyethylene High Density Granulate (HDPE/PE-HD))
	2. Ethylene vinyl alcohol [EVOH] layer	0.175 kg	EVOH (Ethylene vinyl alcohol copolymer
	3. Adhesive Resin Tie-layer [ADMER] layer	0.28 kg	ADMER (Poly(ethylene-alt-maleic anhydride)/ Ethylene-maleic anhydride copolymer)
Logistic	Total segments distance travelled	5,210 km	Truck, Euro 5, 28 - 32t gross weight / 22t payload capacity
Manufacturing	1. Blowmolding	2.71 kWh	Electricity grid mix (IT)
	2. Post cooling	9.3x10-2 kWh	Electricity grid mix (IT)
	3. Welding (hot blade)	9.8x10-2 kWh	Electricity grid mix (IT)
EoL	1) Shredding (within drained vehicle) → Materials separation → Metals recovery and plastic landfill	0.329 kWh	Car shredder; EU-28: Plastic waste on landfill; Electricity grid mix (IT)
	2) Shredding (within drained vehicle) → Materials separation → Metals recovery and plastic incineration	0.329 kWh	Car shredder; U-28: Polyamide (PA) 6 GF30 in waste incineration plant; Electricity grid mix (IT)

Table 92– LCI innovative design solution [2 K Injection molding production technologies].

	Innovative Design		
Life cycle	**Specification**	**Quantity***(per FU)*	**Process** *(GaBi; ecoinvent)*
Materials	1. High-density polyethylene [HDPE] layer	3.006 kg	HDPE (Polyethylene High Density Granulate (HDPE/PE-HD))
	2. Ethylene vinyl alcohol [EVOH] layer	1.179 kg	EVOH (Ethylene vinyl alcohol copolymer
	3. Adhesive Resin Tie-layer [ADMER] layer	0.53 kg	ADMER (Poly(ethylene-alt-maleic anhydride)/ Ethylene-maleic anhydride copolymer)
Logistic	Total segments distance travelled	5,210 km	Truck, Euro 5, 28 - 32t gross weight / 22t payload capacity
Manufacturing	1. Injection upper shell→ Laser welding	1.8 kWh	Electricity grid mix (IT)
	2. Injection lower sheet → Laser welding	1.8 kWh	Electricity grid mix (IT)
	3. Welding (Laser)	2.5x10-2 kWh	Electricity grid mix (IT)
EoL	1) Shredding (within drained vehicle) → Materials separation → Metals recovery and plastic landfill	0.22 kWh	Car shredder; EU-28: Plastic waste on landfill; Electricity grid mix (IT);
	2) Shredding (within drained vehicle) → Materials separation → Metals recovery and plastic incineration	0.22 kWh	Car shredder; U-28: Electricity grid mix (IT); Plastic Incineration

Table 93 - LCI Use phase [fuel tank], vehicle technical data and model parameter.

Technical data referring to car model equipped with the fuel tank		
Vehicle technical characteristic	Vehicle model	FIAT 500X 2,4 litre gasoline
	Vehicle mass	1360
	Emission stage (e.g. EURO5)	EURO 5
	Motorway per-km CO_2 emission [g/km]	143
	Motorway per-km SO_2 emission [g/km]	1.05E-06
	Mixed consumption [l/100km]	8.11

Operation	Vehicle life time [km] - dm	150,000
Analytic model [NEDC]	Mass induced fuel consumption [l/100km*100kg] - FRV_PMR [Gasoline] - fm	0.15
Mass [m]	Vehicle equipped with standard fuel tank [kg]	7
	Vehicle equipped with first innovative fuel tank [kg]	4.715
Fuel density	Gasoline [kg/dm³]	0.74
Specific consumption [kg/kg fuel]	CO_2 emissions generated during the consumption of 1 kg of fuel [kg CO_2/Kg fuel] – f_{CO2}	3.12
	SO_2 emissions generated during the consumption of 1 kg of fuel [kg SO_2/Kg fuel] - f_{SO2}	0.00015

In the modeling of FT life cycle, the following consumptions have been excluded for the following reason:

- packaging consumption: since materials are always recovered for the same purposes;
- invariant component (mounted components, components assembly, helium testing);
- logistic (transport to assembly line and delivery to client): since they have a negligible contribution.

8.2.4.2 LIFE CYCLE IMPACT ASSESSMENT (LCIA)

In this section life-cycle environmental impact has been calculated on the basis of data gathered during the inventory; it has been done by applying *Classification* and *Characterisation* to LCI data according to ISO 14040 standard guidelines. The results of Life Cycle Impact Assessment are reported below; this has been obtained according to *CML 2001 Apr. 2016*regulations, the *Primary Energy Demand (PED)* category from renewable and non-renewable resources (gross cal. value) has been considered. Results are presented in Figure 99 in a form to show, for each class of environmental impact, the contribution of each life cycle stage, on the total impact, for the two design solutions, whereas the total impact percentages delta [Δ%] for each impact indicator are reported in Table 94.

Figure 99 – LCIA Results fuel tank project.

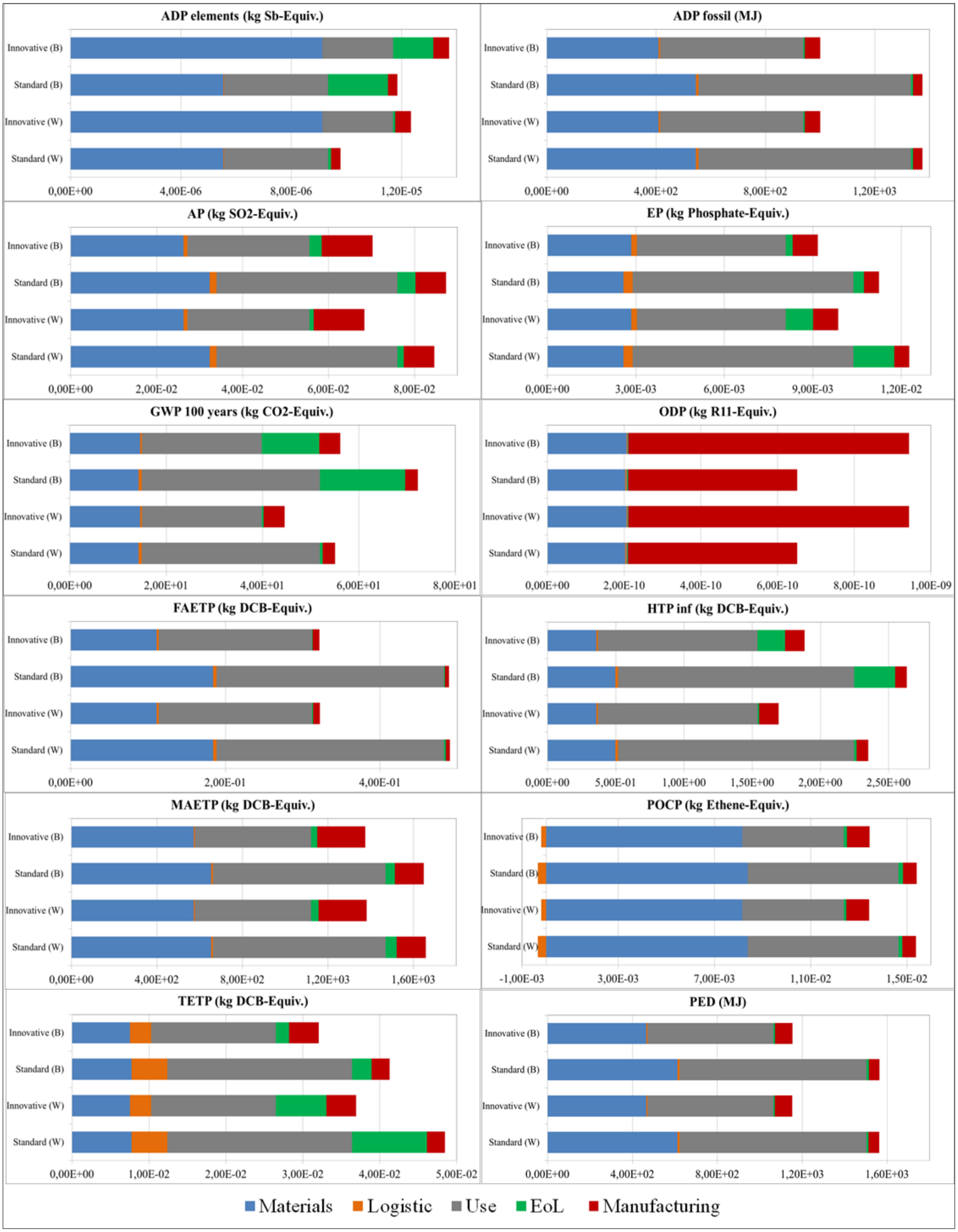


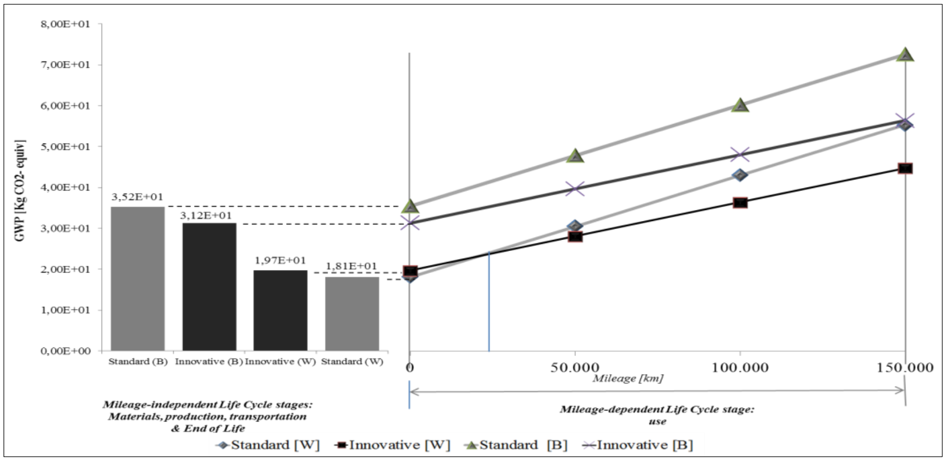
Table 94 – Fuel tank total impact percentage delta decrease (-) increase ( ), worst option (W) and best option.

Impact categories	**Δ% (W)**	**Δ% (B)**
CML2001 - Jan. 2016, Abiotic Depletion (ADP elements) [kg Sb eq.]	21%	14%
CML2001 - Jan. 2016, Abiotic Depletion (ADP fossil) [MJ]	-37%	-37%
CML2001 - Jan. 2016, Acidification Potential (AP) [kg SO2 eq.]	-24%	-24%
CML2001 - Jan. 2016, Eutrophication Potential (EP) [kg Phosphate eq.]	-24%	-23%
CML2001 - Jan. 2016, Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	-52%	-52%
CML2001 - Jan. 2016, Global Warming Potential (GWP 100 years) [kg CO2 eq.]	-24%	-29%
CML2001 - Jan. 2016, Human Toxicity Potential (HTP inf.) [kg DCB eq.]	-39%	-40%
CML2001 - Jan. 2016, Marine Aquatic Ecotoxicity Pot. (MAETP) [kg DCB eq.]	-20%	-20%
CML2001 - Jan. 2016, Ozone Layer Depletion Potential (ODP) [kg R11 eq.]	31%	31%
CML2001 - Jan. 2016, Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	-14%	-14%
CML2001 - Jan. 2016, Terrestric Ecotoxicity Potential (TETP) [kg DCB eq.]	-31%	-29%
Primary energy demand from ren. and non-ren. resources (gross cal. value) [MJ]	-35%	-35%

GHG EMISSIONS BREAK-EVEN

In Figure 100is reported the GHG emissions of CO2 over the life cycle contribution of the standard and innovative auxiliary module. The total amount is separated according to static attribution, accounted for the upstream and downstream activities, with reference of the component operational use. Different conclusion could be made whether the landfill or incineration option is considered. Starting with plastic landfill hypothesis the standard component has a lower CO2 emissions, which the lighter innovate, counterbalance at a vehicle mileage of 22,000 km. Instead, considering incineration option, the lower emissions are associated with the innovative one.

Figure 100 – Fuel tank GHG emissions break-even.



8.2.4.3 LCA INTERPRETATION

From a global point of view, the innovative solution provides a general improvement according to a LCA approach. There are few impact categories, which are negatively influenced by the implementation of the new design proposal as ADPelements and ODP. The reason behind is due to the presence of a major quantity of the toxic EVOH material. The change of manufacturing process lead to a re-composition of the components layers with an increase of EVOH material while lowering Admer and HDPE content. For both solutions, environmental impacts depend mainly on raw materials' ecoprofiles and use phase so the more significant improvement points consist of weight reduction. Even though the minor contribution of manufacturing impact, it is important to underlying the fact that the new injection molding operation is more impacting than the standard blowmolding. Despite the negative influence circumscribed within manufacturing phase, the new technology allowed for the reduction of the leakages point and component weight as to achieve significant weight reduction , which have compensated the negative effect of material and manufacturing impact.

8.2.5 ENVIRONMENTAL LIFE CYCLE COSTING

The following section describes the eLCC analysis of the fuel tank case study.

8.2.5.1 LIFE CYCLE INVENTORY [LCI]

The unit costs are given in Table 95. Regarding the environmental eLCC the total cost is attributed from conventional LCC with the addition of the cost derived by the CO2 emissions generated during vehicle use and their damage cost [€/kg emissions]. Cost of air-pollutant damages were estimated based on:

- Estimated emissions (g/km) both from vehicle operations and all fuel supply activities upstream of the vehicle, and;
- Estimated damage costs (€/g) of CO2 emitted pollutants.

The Clean Vehicles Directive 2009/33 /EC provide valuations of specific environmental damage cost. CO2 emissions were already calculated from LCA analysis.

Table 95 – LCC Inventory standard and innovative fuel tank.

Standard fuel tank			
Life cycle phase	**Flow**	**Unit cost**	**Source**
Transports	Transports (fuel and driver) per km	1.1 €/km	*Primary data*
	Item quantity (standard material)	7 [kg/FU]	
	Truck gross weight	30 [t]	
	Truck payload	22 [t]	
Manufacturing	Electricity	0.12 €/kWh (average European)	*Eurostat, 2018*
	Body blowmolding mold	200.000 €/machine	*Primary data*
	Cooling station support	100.000 €/machine	
	Various molds (clips, valves)	305.000 €/machine	
Use	Gasoline	1.46 €/litre (avg European price)	*IEA, 2018*
	CO_2 emissions cost	4.00×10^{-5} €/gCO_2	*European Commission*
EoL	Electricity	0.12 €/kWh (average European)	*Eurostat, 2018*
	Plastic disposal	0.1 €/kg	*Primary data*
	Electricity consumed for plastic separation	0,047 [Kwh/kg plastic]	

Innovative fuel tank			
Life cycle phase	**Flow**	**Unit cost**	**Source**
Transports	Transports (fuel and driver) per km	1.1 €/km	*Primary data*
	Item quantity (innovative)	4,72 [kg/FU]	
	Truck gross weight	30 [t]	
	Truck payload	22 [t]	
Manufacturing	Electricity (cost)	0.12 €/kWh (average European)	*Eurostat, 2018*
	Superior body half mold	590.000 €	*Primary data*
	Inferior body half mold	540.000 €	
Use	Gasoline	1.46 €/litre (avg European price)	*IEA, 2018*
	CO_2 emissions cost	4.00×10^{-5} €/gCO_2	*European Commission*
EoL	Electricity	0.12 €/kWh (average European)	*Eurostat, 2018*
	Plastic disposal	0.1 €/kg	*Primary data*
	Electricity consumed for plastic separation	0,047 [Kwh/kg plastic]	

8.2.5.2 LCC IMPACT ASSESSMENT [LCIA]

In Table 96 are presented the total cost attributable to the brake pedal from different perspective, internalizing the cost attributable to user during vehicle use and EoL management to recover and/or disposal the relative materials. Economic assessment results are described according to the following cost categories: materials, manufacturing, transports, use and end-of-life. 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 calculation of each contribution has been accomplished as reported below:

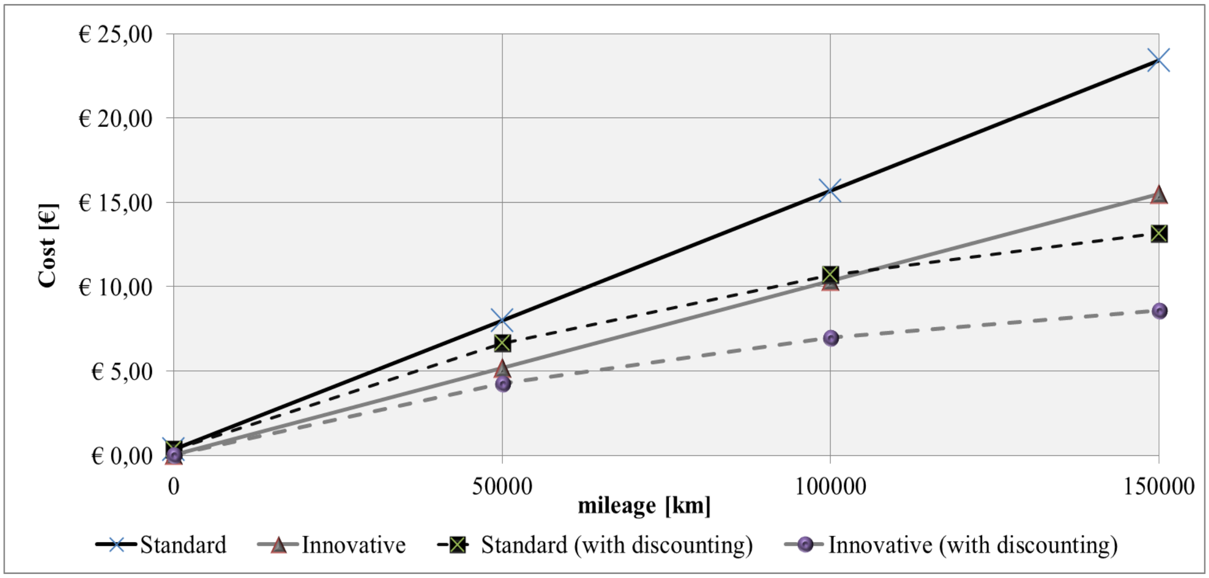
- for materials: the cost of acquisition from suppliers, with the exception of the metal part in the standard brake pedal which consider the acquisition of the metal item;
- for transport: the incidence of the cost per km multiplied by the total distance traveled and divided by truck payload capacity;
- for manufacturing: the cost attributable to each production item considering the contribution of direct labour and machine costs;
- for use: the total fuel consumption during vehicle life-time mileage of 150,000 km attributable to each component, multiplied by the average European cost of gasoline fuel;
- for EoL: the cost attributable to the disposal and/or recovery of each material flow within the dismantle line of vehicle.

Table 96 – eLCC results for fuel tank.

Reference	Flow	Standard unit cost	Innovative unit cost
Transport	Distance travelled	*€ 1,34*	*€ 0,90*
Manufacturing	Investment	*€ 3,36*	*€ 6,28*
	Production	*€ 0,35*	*€ 0,01*
Total cost (MM perspective)		***€ 5,05***	***€ 7,19***
Use	Fuel (150.000 km)	*€ 23,07*	*€ 15,48*
	Externalities	*€ 0,0022*	*€ 0,0018*
Total cost (user perspective)		***€ 23,07***	***€ 15,48***
EoL	Materials separation	*€ 0,04*	*€ 0,03*
	Materials recovery/dispose	*€ 0,70*	*€ 0,42*
Total life cycle cost		***€ 28,86***	***€ 23,11***

Figure 101depicts the fuel consumption cost break-even analysis over the vehicle 150,000 km mileage of use. A sensitivity analysis reporting a comparison among discounting and non-discounting calculation has been accomplished. From the line chart could be observed a break-even point since the economic convenience of the innovative fuel tank production starts from production stage.

Figure 101 – Fuel cost break-even fuel tank.



8.2.5.3 eLCC INTERPRETATION

From the eLCC results breakdown could be seen that the major expenditure occurs during use. Conclude different consideration economic consideration cold depending on the specific actor perspective. Indeed the lighter solution offers savings in the innovative case. On the contrary considering company perspective the investment of the new manufacturing scaled to the component are not so convenient afterward. Considering the full environmental cost, the innovative design offers a discount of 20%. Despite the completeness of the analysis it is important to underlying that sensible variation could be achieved if accounting materials costs.

9. STRATEGY III: FUNCTIONING TECHNOLOGY VARIATION

In chapter 9 is discussed with major details each steps of the analysis for the specific component regarding technology variation strategy. The structure is presented according to the ISO 14040 for LCA and eLCC respectively. To start, a brief description of the “goal and scope” of the study is presented, providing an explanation of component functionality and location within vehicle system. The following studies regard the assessment of a current component design (named standard) with a novel proposal (named innovative). Therefore the main results regard the methodology applicability in terms of data availability, indicators relevance and appropriateness, and results presentation and interpretation are presented. Outcomes in terms of component sustainability could be retrieved only concerning environmental assessment; however more insights could be obtained in a comparative analysis.

9.1 HEADLIGHT AUXILIARY MODULE PROJECT

This project focuses on the environmental impact assessment analysis between *two different lighting technologies* of a specific auxiliary module, performing the same lighting function. The method adopted is the ***Life Cycle Assessment (LCA)*** as a part of Life Cycle Sustainability Assessment (LCSA) analysis. The purpose is to make evidence on which of the two technologies cause mostly the environmental impact, considering the full product life cycle. For this purpose, the perimeter of the analysis include all the phases upstream and downstream of the components production, performing in this way what is so called “cradle to grave” approach analysis. Overall, the main goals of the project are:

- verify applicability of LCA as a supporting tool to “identify the main sustainability hotspots in the product life cycle - especially regarding its technology function during its operation on the vehicle - therefore guide strategy development” and provide elements for production decisions for auxiliary module production;
- develop data collection on environmental impact of auxiliary module of different lighting technology;
- create a model for a method to accomplish the LCA of light sources;
- provide guidance on different product design proposals based on environmental impact point of view.

9.1.1GOAL AND SCOPE DEFINITION

The scope of the present study is to assess the environmental impacts of an auxiliary module in view of "cradle to grave" approach. The strategy driver taken into account is the technology operation improvement, leading to *less energy demanding during component operation*, while performing the same lighting function. The present analysis can be used to supply sustainability information to improve product performances in terms of:

- life cycle perspective to assess a balance among environment point of view;
- respect of environmental legislative compliance;
- demonstrating a commitment by manufacturers to stakeholders for the responsible development of MM products;
- quantifying energy and resource intensive processes and minimizing their impact.

In order to assess the environmental impact of the innovative technology to be implemented in the auxiliary module, a comparative LCA between the two different design solutions has been accomplished. The main technical difference data of the two design solutions are reported in Table 97. The consequences of technology variation are: the increase of the entire mass weight of the auxiliary module system, the sub-components (listed in Table 97) variation and therefore component manufacturing and logistic changes. For the comparative analysis, only the sub-components that differ from the two design solution have been taken into account.

Table 97 – Technical data of auxiliary module design solutions.

Features	Standard	Innovative	Variation
Weight (kg)	0.3	0.44	32% weight increase
Parts	Auxiliary module with halogen turn indicator, LED Daytime running /position light	Auxiliary module with turn indicator, LED Daytime running /position light	Variation of light components typology. Standard *(halogen and one LED)* and innovative *(several high power LEDs)*
	1. Inner lens; 2. Mounting piece; 3. Lamp socket; 4. Bulb PY; 5. Adapter plate; 6. Reflector TI/DRL; 7. DRL/POS light	8. Light guide; 9. Reflector; 10. Retaining plate; 11. Adapter; 12. Heat sink; 13. Gasket	Sub-components and geometry
Lighting function	Halogen Reflector	Light-guide LED	Different lighting function source

In fact, the headlight system consists of a very high number of sub-components. The exploded views of the entire headlights (where the auxiliary module is integrated) are reported in Figure 102 and Figure 103.

Figure 102 – Standard headlight system exploded view.

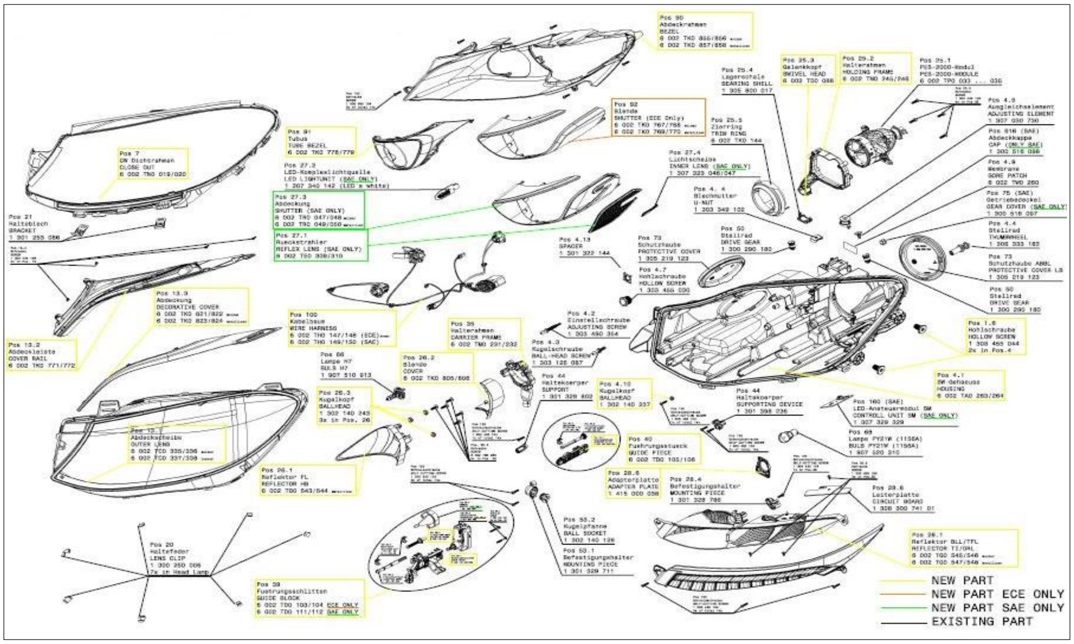
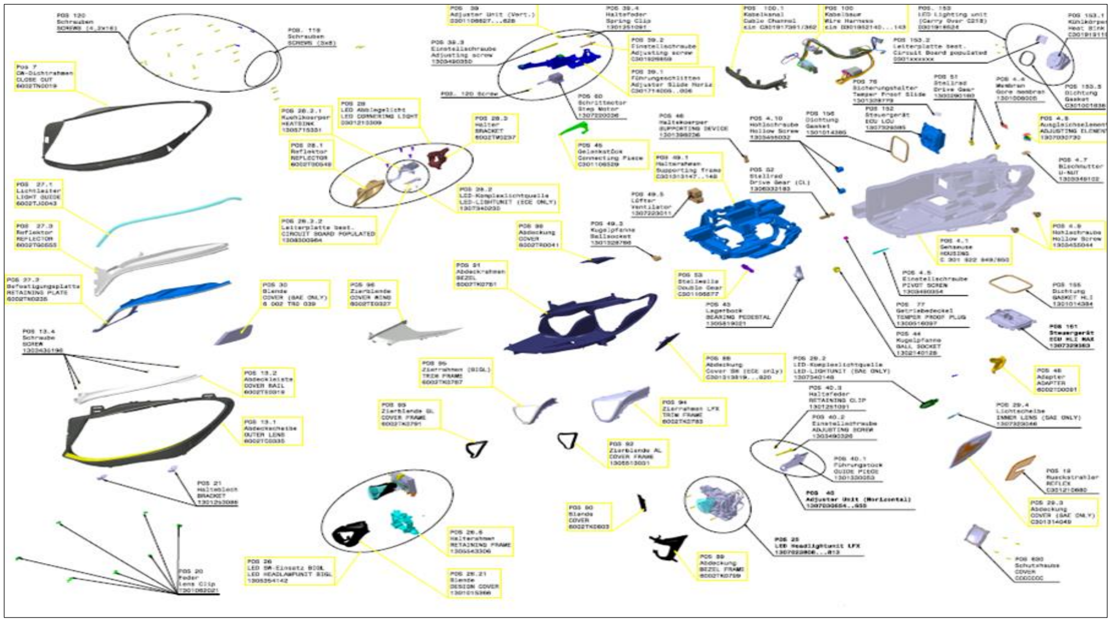


Figure 103 - Innovative headlight system exploded view.



9.1.2 COMPONENT DESCRIPTION

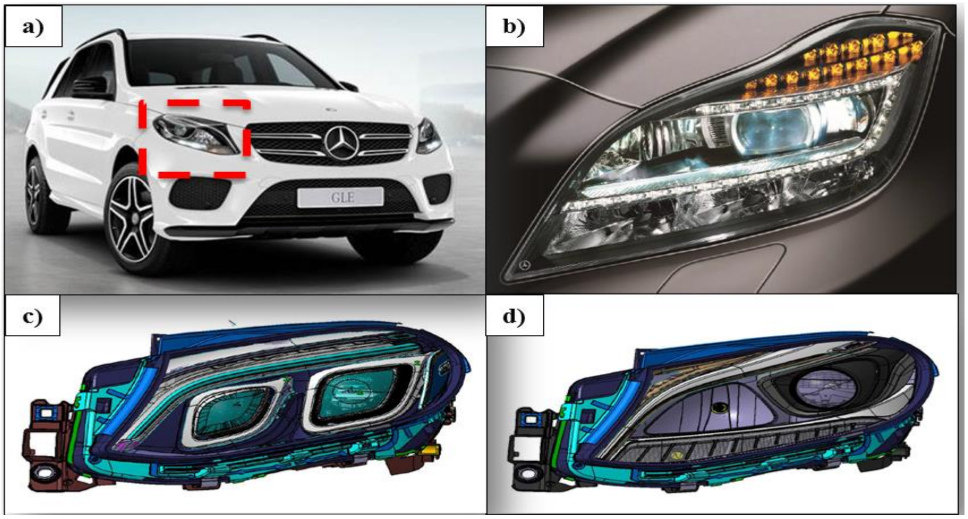
The lighting system of a vehicle consists of lighting and signalling devices mounted or integrated to the front, rear and sides. This lights the roadway for the driver and increases the conspicuity of the vehicle, allowing other drivers and pedestrians to see a vehicle's presence, position, size, direction of travel, and the driver's intentions regarding direction and speed of travel. Overall, the lighting and signalling function of the lighting system are listed in Table 98. Figure 104 reports the vehicle selected to integrate the new design proposal, as well as the drawing of the standard and innovative headlights system, where the auxiliary module is integrated.

Table 98 - Lighting and signalling functions for a vehicle system.

1) Lighting functions (to illuminate the road):
•Low Beam (Passing beam) (Dipped-beam); *•High Beam (Driving beam) (Main-beam).*
2) Light-signalling functions (to be seen):

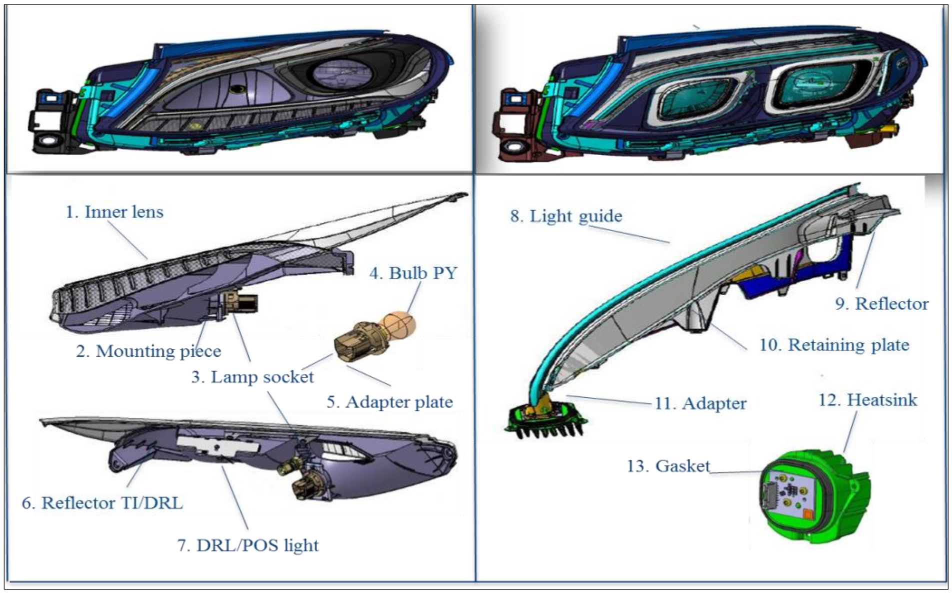
- *Direction-indicator lamp;*
- *DRL (Daytime Running Lamp);*
- *Front position lamp;*
- *Side marker lamp (NAFTA);*
- *Side reflex (NAFTA);*

Figure 104 – a) Reference vehicle selected equipped with the headlight module; b) innovative headlight module; c) standard drawing design and d) innovative drawing design.



The different lighting function technology leads to a variation of the numbers of parts which the module is consisted. Those sub-components are listed in Table 97 and depicted in Figure 105.

Figure 105 - Headlight's subcomponent variation for standard design [halogen technology] (sx) and innovative design [LED technology] (dx).



9.1.3 SYSTEM BOUNDARIES AND FUNCTIONAL UNIT

In this paragraph, the product system and the system boundaries are described. Regarding the system boundary, LCA is conducted by defining product systems as models that describe the key elements of physical systems. The system boundary defines the unit processes included in the system. Ideally, the product system is modelled in such a manner that inputs and outputs at its boundary are elementary flows. The choice of the elements of the physical system modelled depends on the goal and scope definition of the study.

The two auxiliary modules are analyzed as integrated within the headlamp system through all its life cycle, according to a "cradle to gate" approach, splitting it in the following macro-phases: materials, manufacturing, use, end of life and transport of each phase in between.

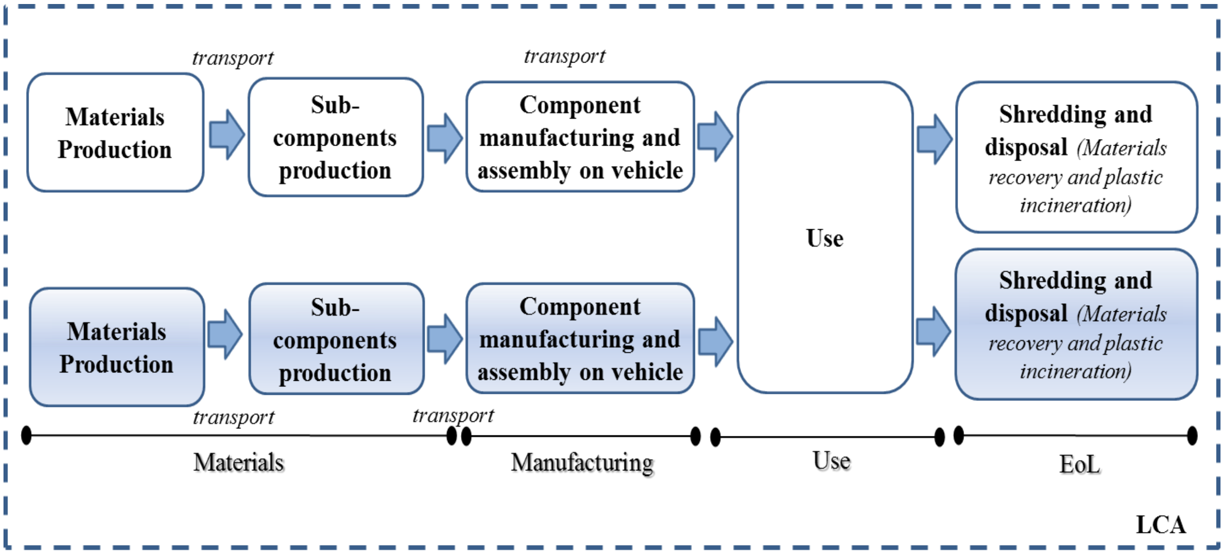
For the present case study are considered the life cycle phase grouped according to:

- production which includes raw materials extraction and their processing, as well as for component manufacturing;
- use is based on component operation within the reference vehicle selected for a specific life time mileage;
- end of Life: consists of all the process involved to recover/disposal of the materials (after vehicle dismiss) according to their typology.

Following Figure 106characterizes auxiliary module life cycle phases for both scenarios. The two design solution differs for the "material, manufacturing and transport of these two phases in between".

The Functional Unit (FU) of the present analysis is an automotive auxiliary module integrated within Headlamp system, supporting and housing all the instrumentation for vehicle use, to be mounted on Mercedes-Benz GLE 400 4Matic Sport [gasoline; 333 HP; 2,996 cc], for an operating time of 12000 h, with a life-distance of 150,000 km.

Figure 106 – Auxiliary module case study system boundary.



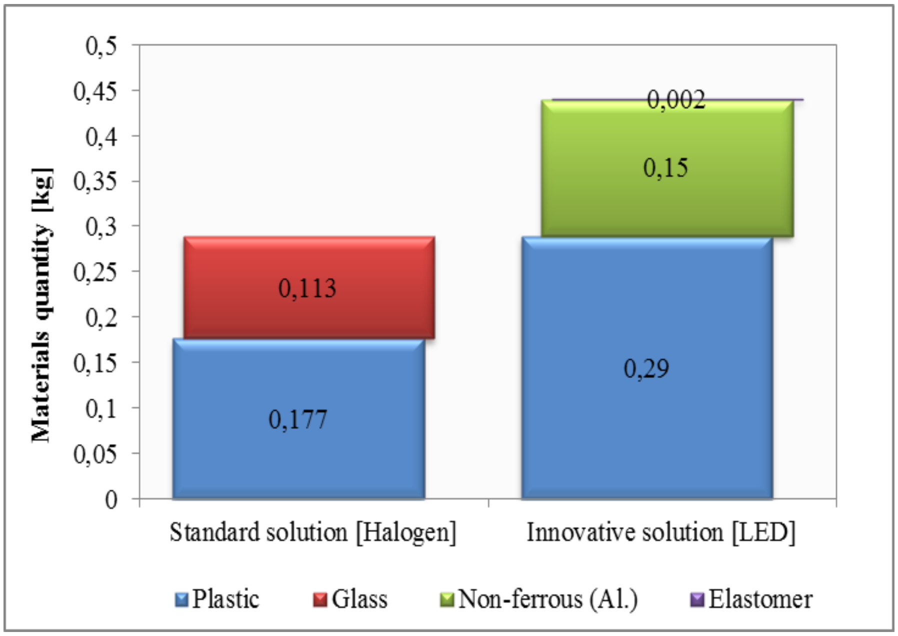
9.1.5 LCA ANALYSIS

Hereafter is describing in details each step of the LCA analysis.

9.1.5.1 LIFE CYCLE INVENTORY (LCI)

In this sub-paragraph data collection to quantify relevant inputs and outputs of the phases which compose product life cycle is described. Where possible process parameters (materials and energy flows) were obtained by direct measurements on industrial processes and/or estimation; in the others cases assumptions from GaBi 6.115 processes database have been used. In Table 100and Table 101 a description of modalities used to collect data is reported. For this comparative assessment, only the sub-components variants have been taken into account. The materials compositions and production are grouped with the reference of Gabi datasets and data quality. Overall, the composition of the materials used for the production of the two auxiliary modules designs is described in Figure 107. In the standard solution the plastic quantity does not over exceed the 0.177; whereas in the innovative solution plastic quantity is increased of 64%. Glass parts are eliminated and are substituted with aluminum and a slight percentage of elastomer.

Figure 107 - Materials composition breakdown.



The Use stage covers the operation of the auxiliary module integrated within the headlamp unit of the vehicle selected. It reflects the fuel consumption linked to the mass and the electricity consumption during the life time of a vehicle. It is assumed, that the headlamp unit does not require exchange or maintenance in the considered life span.

To calculate the environmental impact imputable to the auxiliary module during the whole vehicle life time [150,000 km reference and headlamp operating time of 12,000 h, it was used an analytical model proposed by (Koffler and Rohde-Brandeburger 2010), that scales the fuel consumption attributable to the mass of the component (mass induced-fuel consumption factor) and to the component operation during the different energy absorption of lighting module. Therefore, for theis specific case study, the calculation of fuel consumed is based on the mass-induced fuel consumption starting from:

– The amount of work necessary to move 100 kg on a specific driving cycle;

– The differential efficiency of the internal combustion engine.

Mass of fuel consumption (m_{fuel}) is calculated through the following equation X:

$$m_{fuel} = m_c \text{ x } f_m \text{ x } d_m + P \text{x } f_e \text{ x } d_e \qquad (eq.\ X)$$

where:

- m_{fuel} = represent the fuel consumption during the entire vehicle life-time attributable to the auxiliary module ;
- m_c = mass of the auxiliary module for both cases;
- f_m = is the mass-induced fuel consumption for a naturally aspired gasoline car through the New European Driving Cycle (NEDC);
- P = electric power of the lighting technology for both cases;
- f_e =is the electricity-induced fuel consumption for a naturally aspired gasoline car through the New European Driving Cycle (NEDC);
- d_e = Headlight operation [km] based on 33,6 km/h avg. speed in NEDC.

The amount of emissions [CO_2 and SO_2] during the entire vehicle lifetime attributable to the auxiliary module support is calculated by the following equation:

$$emissions_{CO2} = m_{fuel} * f_{CO2} \qquad \text{(eq. X)}$$

$$emissions_{SO2} = 2 * m_{fuel} * f_{SO2} \qquad \text{(eq.Y)}$$

- $emissions_{CO2}$= emissions of CO_2 pollutant during the entire vehicle life-time attributable to the component mass weight (kg);
- m_{fuel} =represent the fuel consumption during the entire vehicle life-time attributable to the auxiliary module;
- f_{CO2} = CO_2 emissions generated during the consumption of 1 kg of fuel [kg CO_2/Kg fuel];
- $emissions_{SO2}$ = emissions of SO_2 pollutant during the entire vehicle life-time attributable to the component mass weight (kg);
- f_{SO2} = SO_2 emissions generated during the consumption of 1 kg of fuel [kg SO_2/Kg fuel].

As the model scales the emissions linearly with the fuel consumption attributable to the component, only the usage emissions that directly depend on the amount of fuel consumption CO2 is considered in the assessment. For the modeling of the use phase, a reference vehicle with the same technical characteristics of the car on which the auxiliary module is installed has been selected and reported in Table 99.

Table 99 - LCI Use phase [auxiliary module], vehicle technical data and model parameter.

Technical data referring to car model equipped with the auxiliary module		
Vehicle technical characteristic	Vehicles model	Gasoline; 333 HP; 2,996 cc
	Emission stage	5
	Vehicle mass [kg]	2055
	Motorway per-km CO_2 emission [g/km]	204
	Mixed consumption [l/km]	9
Operation	Vehicle life time [km] -**dm**	150,000
	Headlight operation [km] based on 33,6 km/h avg. speed in NEDC - **de**	100806
Analytic model [NEDC]	Mass induced fuel consumption [l/100km*100kg] - FRV_PMR [Gasoline] - **fm**	0.15
	Electricity induced fuel consumption [l/100W/100km] [Gasoline] - **fe**	0.13
Mass [m]	Headlight equipped with Halogen auxiliary module [kg]	0.3
	Headlight equipped with LED auxiliary module [kg]	0.44
Electric Power [P]	Power Halogen [W]	23.31
	Power LED [W]	12.6
Mass induced fuel consumption	Halogen [l/100km]	0.001
	LED [l/100km]	0.001
Fuel induced fuel consumption [f_e]	Halogen [l/100km]	0.030
	LED [l/100km]	0.016
Fuel density	Gasoline [kg/dm^3]	0.74
Specific consumption [kg/kg fuel]	CO_2 emissions generated during the consumption of 1 kg of fuel [kg CO_2/Kg fuel] **–** $\mathbf{f_{CO_2}}$	3.12
	SO_2 emissions generated during the consumption of 1 kg of fuel [kg SO_2/Kg fuel] **–** $\mathbf{f_{SO_2}}$	0.00015

The EoL management options have been modeled according to the auxiliary module materials composition to recover:

- *Non – ferrous materials :* metal recovery process → screening → magnetic separation → eddy current → inductive resonance → ballistic separation [to separate aluminium];
- *Plastics, elastomers, and electronics*: from metal recovery process → fluff treatment in press machine [to obtain compacted fluff].

Energy consumption calculation is based on the mass of the sub-component to be treated according to the EoL options to recover/dispose certain material typology. Materials have been classified according to: *non-metals* for aluminium content materials and *others* for plastics, electronics and elastomers. The End of Life modelling includes the environmental burdens of recycling processes and grants credits for the recycled/ recovered materials.

Table 100 – LCI standard design solution [Halogen technology].

	Standard Design		
Life cycle phase	**Specification**	**Quantity** *(per FU)*	**Process** *(GaBi; ecoinvent)*
Materials and production	PC Makrolon 2447	1.13E-01	EU-28 Float flat glass
	POM C9021 white	2.00e-03	*DE* Polyoxymethylene granulate (POM)
	PBT	2.00E-03	DE -Polybutylene Terephthalate Granulate (PBT)
	Glass, Steel	3.00E-03	Al2O3; AlMg3; Cu99;CuSn6; D5S lamp-PCB populated; EN AW-AlMg1; EN AW-AlMn1Mg; Polytetrafluoroethylene granulate (PTFE); Ferrite NiZn; galv. Ag (Hartsilber) (galvanischabgeschiedene Silberschicht); galv. Ni (Halbglanznickel) (galvanischabgeschieden); galv. Ni (Halbglanznickel) (galvanischabgeschieden); MolybdenumUnalloyed, Low Carbon (365); Ni99,2; NiMn; PBT; PPSGF40; Quarzglass; VQM; X5CrNi18-10; X6Cr17; EU - 27 Polyurethane (PU, PUR) semi-rigid from rape seed
	APEC 1695/Grey	1.65E-01	DE Polycarbonate Granulate (PC) *[for the main component]* and EU-27 Aluminium clean scrap remelting & casting (2010); DE Argon [gaseous]; EU-28 Tap water; DE Silicon rubber [RTV-2,condensation]; EU-28 Compressed air [10 bar, low efficiency]; EU-28 Electricity grid mix 1kV-60kV *[for metallization]*
	PBT GF30	5.00E-03	MM- Polybutylene terephthalate with 30% of glass fibers [PBTGF30]

EoL	1) Shredding (within drained vehicle) →Materials separation → Non-metals recovery and plastic incineration	0.0157 MJ	a) Non-ferrous metal recovery and glass recovery [EU-27: Waste incineration of glass/inert material]; b) Plastic recovery and incineration [U-27: Waste incineration of plastics (PET, PMMA, PC)]

Table 101 - LCI innovative design solution [LED technology].

	Innovative Design		
Life cycle phase	**Specification**	**Quantity** *(per FU)*	**Process (GaBi; ecoinvent)**
Materials and production	PMMI	4.80E-02	RER Polymethylmethacrylate-sheet (PMMA)
	PC	1.23E-01	DE Polycarbonate Granulate (PC) *[for the main component]* and EU-27 Aluminium clean scrap remelting & casting (2010); DE Argon [gaseous]; EU-28 Tap water; DE Silicon rubber [RTV-2,condensation]; EU-28 Compressed air [10 bar, low efficiency]; EU-28 Electricity grid mix 1kV-60kV *[for metallization]*
	PCB Single FR4 Epoxy Sheet, Copper, LED's	1.12E-01	DE Polycarbonate Granulate (PC)
	PBT	7.00E-03	DE Polybutylene Terephthalate Granulate (PBT)
	GD AlSi12 (Cu)	1.50E-01	MM - Aluminium AlSi12(Cu) [Pressure Die Casting and Production]
	Silicon shore 50 A	2.00E-03	DE Silicon rubber [RTV-2, condensation]
EoL	1) Shredding (within drained vehicle) → Materials separation → Non-metals recovery and plastic incineration	0.0235 kWh	a) Non-ferrous metal recovery and aluminium credit [EU-15: Low copper aluminium scrap credit]; b) Plastic recovery and incineration [U-27: Waste incineration of plastics (PET, PMMA, PC)]

In the modeling of auxiliary module‘s life cycle, the following consumptions have been excluded for the following reason: i) packaging consumption: since materials are always recovered for the same purposes, ii) invariant component and logistic.

9.1.5.2 LIFE CYCLE IMPACT ASSESSMENT (LCIA)

The results of Life Cycle Impact Assessment are reported below; this has been obtained according to *CML 2001 Apr. 2016*regulations, the *Primary Energy Demand (PED)* category and the *Total freshwater consumption (including rainwater) [kg]*. Results are presented in Figure 108 in a form to show, for each class of environmental impact, the contribution of each life cycle stage, on the total impact, for the two design solutions, whereas the total impact percentages delta [Δ%] for each impact indicator are reported in

Table **102**.

Figure 108 – LCIA Results for standard and innovative design.

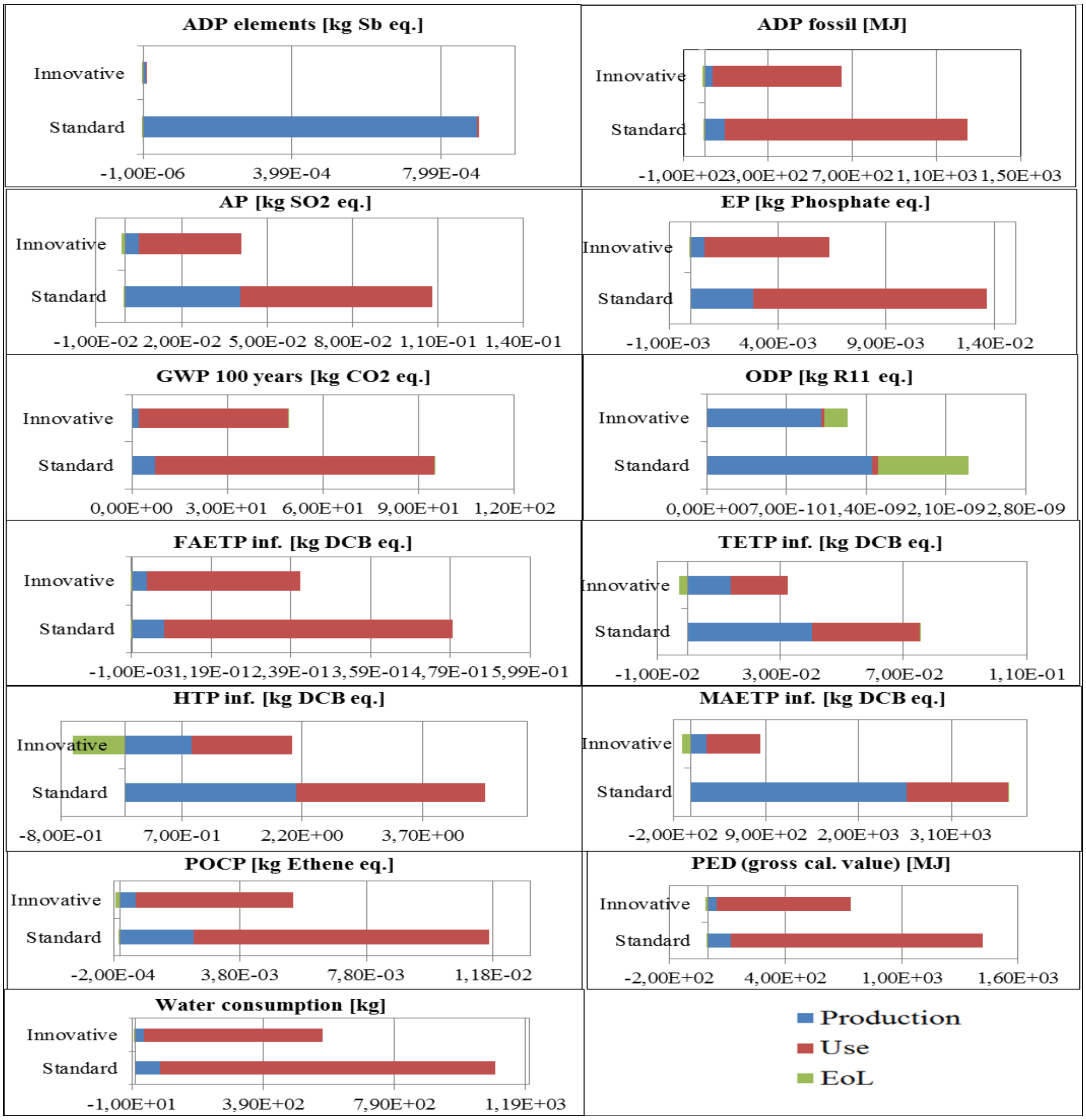


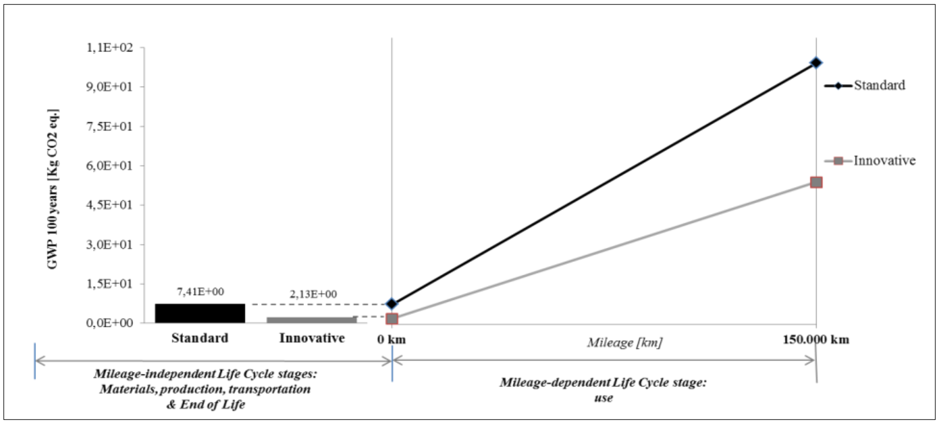
Table 102 – Auxiliary module total impact percentage delta decrease (-) increase ( ).

Impact categories	Δ %
CML2001 - Jan. 2016, Abiotic Depletion (ADP elements) [kg Sb eq.]	-99%
CML2001 - Jan. 2016, Abiotic Depletion (ADP fossil) [MJ]	-48%
CML2001 - Jan. 2016, Acidification Potential (AP) [kg SO2 eq.]	-63%
CML2001 - Jan. 2016, Eutrophication Potential (EP) [kg Phosphate eq.]	-54%
CML2001 - Jan. 2016, Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	-50%
CML2001 - Jan. 2016, Global Warming Potential (GWP 100 years) [kg CO2 eq.]	-49%
CML2001 - Jan. 2016, Human Toxicity Potential (HTP inf.) [kg DCB eq.]	-68%
CML2001 - Jan. 2016, Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	-81%
CML2001 - Jan. 2016, Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	-46%
CML2001 - Jan. 2016, Photochemical. Ozone Creation Potential (POCP) [kg Ethene eq.]	-54%
CML2001 - Jan. 2016, Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	-61%
Primary energy demand from ren. and non-ren. resources (gross cal. value) [MJ]	-49%
Total freshwater consumption (including rainwater) [kg]	-49%

GHG EMISSIONS BREAK-EVEN

In Figure 109 is reported the GHG emissions of CO2 over the life cycle contribution of the standard and innovative auxiliary module. The total amount is separated according to static attribution, accounted for the upstream and downstream activities, with reference of the component operational use. The standard component accounts for 7.41 kg of CO2 emissions without considering component operation. On the contrary the emissions generated in the innovative solution activities are ¼ less. At the end of component operation, considering the vehicle total distance travelled of 150,000 km, the discrepancy among standard and innovative design is reduced, passing from 71% to 42%.

Figure 109 – GHG emissions break-even graph.



9.1.5.3 LCA INTERPRETATION

In this final section the results obtained and previously shown for each process separately are now compared and interpreted.

The substitution of the lighting technology, causes an overall impact decreases ranging between 46% and 99%. The most outstanding reduction observed regards the following impact categories: ADP elements (-99%), followed by the toxicity categories of MAETP (-83%) and HTP (-70%). Each impact indicator is representative for a specific environmental issue and it is generally influenced by a specific portion of product life cycle. In the specific case regarding the vehicle operation (use), the impact categories affected are respectively: GWP, POCP, PED and EP.

Although the headlight equipped with LED technology is heavier in weight, the energy absorbed during its operation is minor compared to the Halogen. For that reason, the environmental impact of the LED use is decreased. The production impact is more relevant for the remaining impact categories, especially ADP elements, ODP, FAETP, and POCP. What cause the most impact in the halogen technology are the materials that constitute the lamp, especially the Aluminum-manganese alloy and electronics. EoL presents a minor contribution to the total components life cycle impact. Despite the negligible effect over the entire life cycle, it is important to underling the slight advantages that the innovative design brings in terms of impact reduction in the EoL contribution. Even though the energy expenditure is higher in the EoL innovative headlight; the greater amount of materials recovery for plastic incineration, allow for a major electricity and energy production. Overall, the two major contributions, in terms of life cycle phase incidence, are attributed to the production (material consumption) and component operation (use category). The use stage accounts for the majority of the environmental impacts due to the energy consumption and emissions release, while EoL causes only fairly marginal total life cycle impacts.

The environmental impacts of light sources are generally clearly dominated by the energy consumption in the use. Thus, the potential environmental impacts of the light source are strongly dependent on the choice of the energy source. That is the reason for considering PED as a representative parameter for the measurement of the total energy expenditure.

10. FINAL REMARKS

In chapters 7, 8 and 9 have been discussed in deep each design strategies, presenting the relative case study applications. All of these analysis have been conducted with the scope of acquire more knowledge on the properties of certain materials when employed for a specific function and purpose. Indeed this novel database of information could be used as a key-instrument when applying a certain strategy of a specific component to balance among technical and environmental targets. It has be seen the birth a new way of using certain materials, like plastic, in a new field like powertrain motors and so far… For sure, this intentions should be supported by a continues investigation on technology developments. Indeed the is plenty of further improvements on this sectors that could be obtained with a more conscious combination of the use of novel materials and technology. The use of a specific manufacturing procedure could be extended to other product when optimization in terms of energy expenditure, time and economic could be perceived. For instance the use of a blowmolding technology to work a piece of plastic (chapter 8), or a electronic technology (chapter 9).

All of these case studies discussed should offer the opportunity to give more knowledge on the potential of use certain materials and technology in the field of automotive and beyond. Despite a certain strategy has been tested for a specific purpose, a different employment should not be excluded. As an example the natural fibers could be tested for other plastic components application, when functional requirements are not so that restringing. Moreover a combination of two strategies as technology and material variation could lead to a better target than when are considered disjointed, this is the case of the use of injection molding technology to produce a plastic compound for powertrain use with the further adoption and adjustment of component miniaturization.

This chapter summarizes all the LCA results obtained in the previous chapters 7 and 8 of all the case studies application. For each impact category the various modules were grouped together and specifically according to the attribution of the reference solution (standard) with the alternative (innovative) one. For each individual component, the impact considered concerns the sum of the contributions of the categories in relation to the behind provenance: materials, manufacturing, use and end of life (considering the landfill case). The selection of the aforementioned classes is because the contribution related to logistics is very negligible. In addition, the logistic management is a variable dependent on strategic choices of potential suppliers' selection, which represent an independent variable contrarily to the materials and associated technology ones. In addition, to assess the magnitude of each impact reduction strategies, a KPI (formula 9) has been calculated, for the category influenced by lightweighting strategy; in fact, this formulation evaluates the relationship between the difference impacts resulting from the mass reduction. The only component excluded in this argument is the auxiliary module for reasons related to its purpose, namely the environmental benefit linked only to an operation and not to a selection of materials or production technology. Unlike the other components, the auxiliary module operates actively during the phase of its use. The other components ensure a passive contribution during vehicle use, since the only incidence is linked to weight.

$$\mathbf{KPI}_{I/M}=\frac{\boldsymbol{\Delta}\mathbf{indicator}}{\boldsymbol{\Delta mass}} \qquad (9)$$

Where:

- $\Delta_{\text{indicator}}$= Impact $_{\textit{indicator standard solution}}$ – Impact $_{\textit{indicator innovative solution}}$;
- Δ_{mass}= Mass $_{\textit{standard solution}}$ – Mass $_{\textit{innovative solution}}$.

To conclude a diagram, which illustrates all the GHG break-even points of the various case studies, is offered. In order to retrieve additional insights, two sensitivity analyzes have been accomplished. The first evaluates the consequence of different end-of-life scenarios variant, and the second is based on the additional secondary effect results observable during vehicle use as a consequence of component mass decrease. This choice is linked to the fact that the two most incident phases of the impact of all the components is the consumption of materials and the use phase. It is known that the lightening of the component certainly has benefits during use because proportionally reduces tailpipe emissions and fuel consumption; however the lightweighting ensure additional beneficial effects called "*secondary effect*". For these reasons, this effect is evaluated on the GWP indicator.With regard to the materials depletion question, they are heavily dependent on the selection of EoL policies, whether the component is re-used, or materials are recovered. In particular, considering the material recovery, there are several degrees of recovery, which also result in different material quality obtained. For the reasons advanced above 3 possible end-of-life scenarios have been hypothesized, varying metals and non-metals recovery degree and ASR destination.

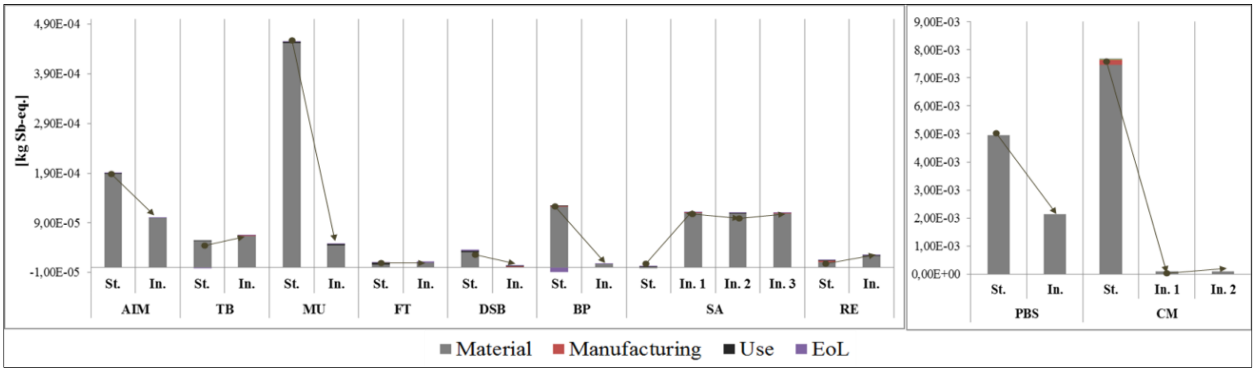
10.1 SUMMARY OF RESULTS

Following are presented a summary of LCA analysis results - which have been displayed in chapter 7 and 8 for a specific project – and here are presented in such a way to group all the projects results for a specific impact category under one single diagram.

10.1.1 ABIOTIC DEPLETION ELEMENTS (ADP$_{\text{elements}}$)

From Figure 110 is evident that ADP$_{\text{elements}}$ indicator is heavily influenced by material impact contribution. Positive responses are observed for the lightweighting strategy application with sharply reduction obtained in: AIM, MU, PBS, BP and CM cases, whereas for other case studies the results are pejorative (TB, SA, RE and FT). Therefor the following consideration can be drawn, which could be useful to reduce the effect of abiotic element consumption. The use of PA6 in substitution of PP is preferable (AIM), reduce material input through a component layout reformulation (MU), consider different typology of plastic filler which are less damaging and allow for a weight reduction as HGS (DSB) and whenever is possible natural fiber instead of synthetic (PBS). Prefer the use of secondary aluminium instead of heavy steel. The replacement of plastic brings benefit when the weight reduction is sharp (CM) otherwise, it might be pejorative for noteworthy incidence (TB and SA). Mind the selection of particular plastic typology, the EVOH is a particularly hazardous plastic (FT), as PEI compared to PES (RE).

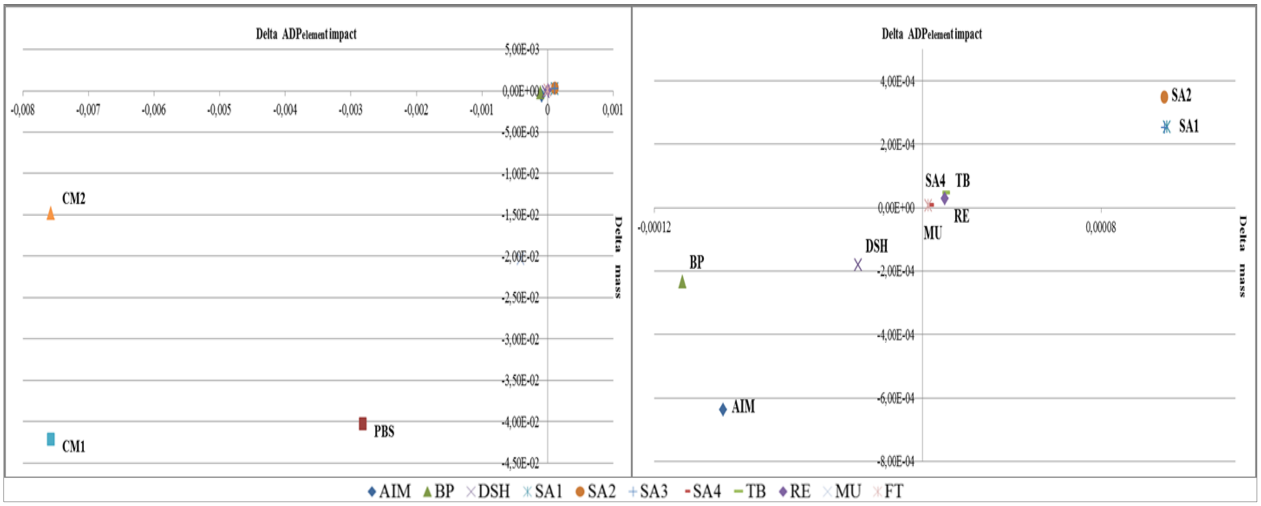
Figure 110 – Summary of $ADP_{elements}$ indicator results.



The lightweighting strategy implementation effect is measured though the KPI calculated using formula 9 with reference on $ADP_{elements}$ numbers. In

Figure 111 is presented a panoramic of the ADP_{KPI} calculated for the projects involved. The major the KPI value is, and the more the strategy is efficacious. The growth of KPI could be obtained maximizing the delta impact reduction and innovative component weight decrease. In this case the most successful case studies applications regard the CM, PBS, PB and AIM.

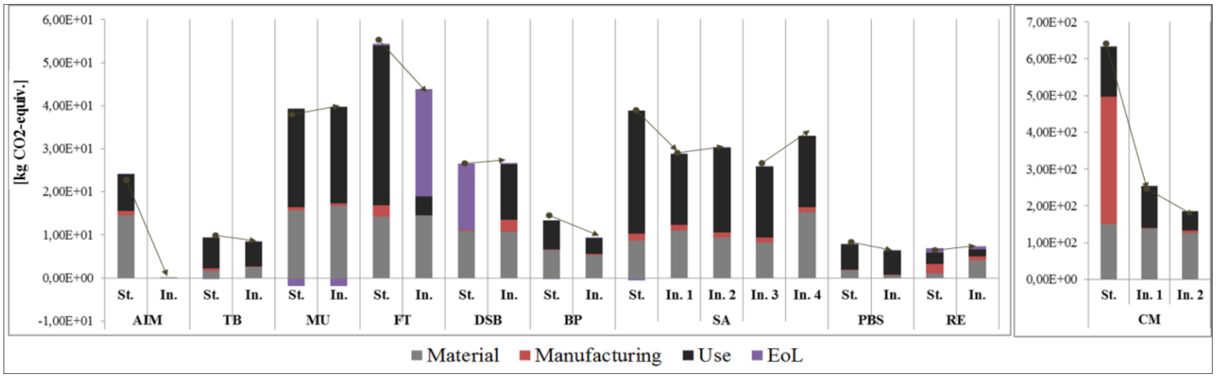
Figure 111 – ADP$_{elements}$ KPI.



10.1.2 GLOBAL WARMING POTENTIAL (GWP$_{100}$)

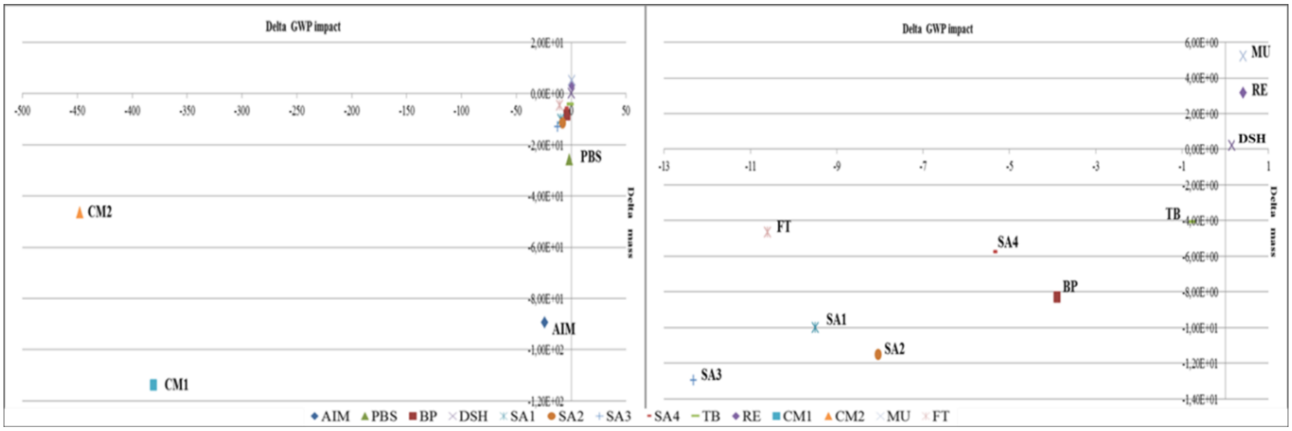
Figure 112 display the results for GWP impact category. In this case, the use stage is more predominant, followed by material consumption. The only exception is linked to the standard CM component whose manufacturing stage involves the expenditure of great amount of electricity, which overcomes all the LC influence. Limited to the use stage the lightweighting effect enhance for GHG emissions reduction. Despite the weight reduction, for some component (MU, DSB, and RE) the innovative proposals increase the GWP indicator. These results are partially caused by the use of materials, such as plastic whose production process require more amounts of electricity and chemicals and for their recovery degree at EoL stage.

Figure 112 - Summary of GWP$_{100}$ indicator results.



The KPI results indicated in Figure 113 reveal that the most effective strategy to enhance GWP reduction is the component mass decrease. The highest performances are observed for the component with the highest weight decrease percentage.

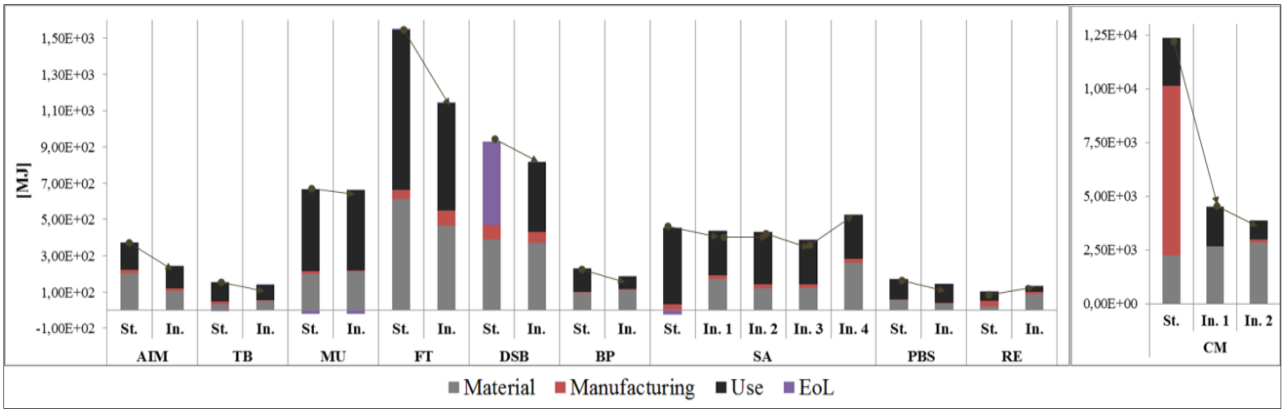
Figure 113 – GWP$_{100}$ KPI.



10.1.3 PRIMARY ENERGY DEMAND (PED)

Observing PED results grouped in Figure 114, the same considerations made for GWP could be retrieved, since the predominant LC phase is the use followed by material but with a major magnitude registered for PED indicator.

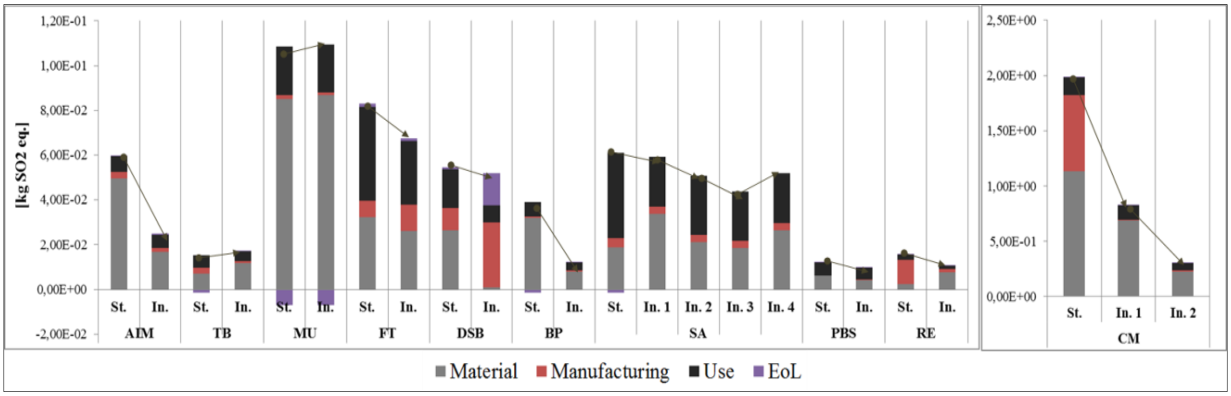
Figure 114 - Summary of PED indicator results.



10.1.4ACIDIFICATION POTENTIAL (AP)

AP results are collected in Figure 115. Here manufacturing show a major influence, since in the production of electricity are generated great amount of SO_2 emissions. However, the greatest part of emissions is spawned during material production and use stage. Only the TB, MU and SA4 have a pejorative marks due to the selection of a specific class of material whose production process require more amount of electricity compared to the references ones.

Figure 115 - Summary of AP indicator results.

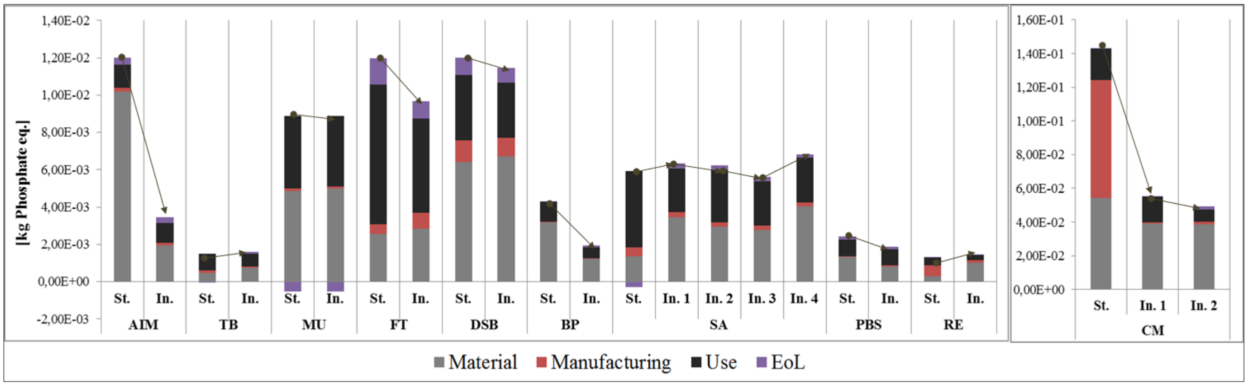


10.1.5EUTROPHICATION POTENTIAL (EP)

Below

Figure 116 summarizes the EP indicator. Results reveal that the predominant LC contribution is attributed to material followed by use. An exception is related to the CM case study since manufacturing stage is highly influencing for the excessive withdraw of electricity. Apart from that, the FT component shows a relevant contribution on use rather than on materials. Considering the full impact of each component, the EP of the innovative solution is reduced, not including the throttle body. Considering the impact of materials production the use of plastic is indeed pejorative compared to the use of metals. Moreover the are typology of plastic which worsen even more than other does, such as PA6 rather than PP (AIM). Those considerations should be applied based on the material quantity, in fact if a relevant quantity decrease is obtained the solution is in favor of the adoption of plastic rather than metals (PB, CM).

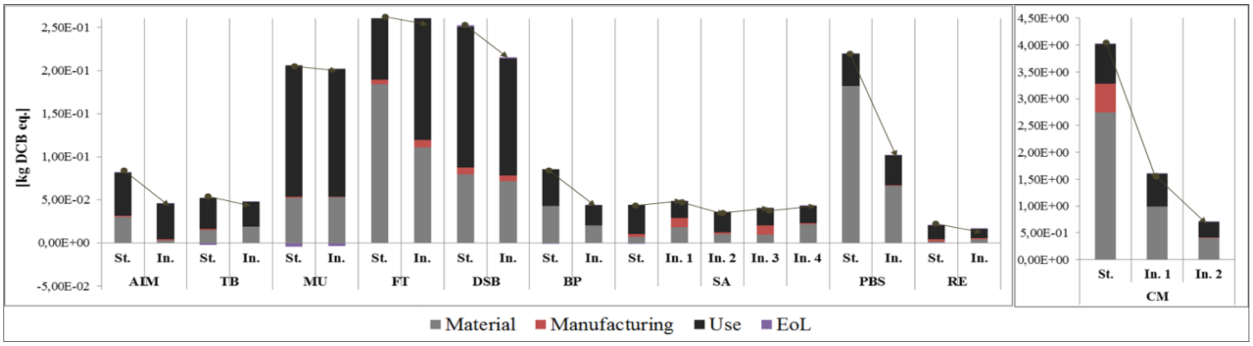
Figure 116 - Summary of EP indicator results.



10.1.6 FRESHWATER AQUATIC ECOTOXICITY POTENTIAL (FAETP$_{inf.}$)

The total project impact of the FAETP is reported in Figure 117. Diverse concern regards this topic whether the component is heavyweight; since this, ones display high use phase influence (MU, FT, DSB). On the contrary, the remaining contribution is attributed to the material exploitation. Indeed when natural material (NF) substitute, the synthetic is the impact of material sharply decrease (PBS). To sum up the innovative solutions are all in favor of FAETP indicator reduction.

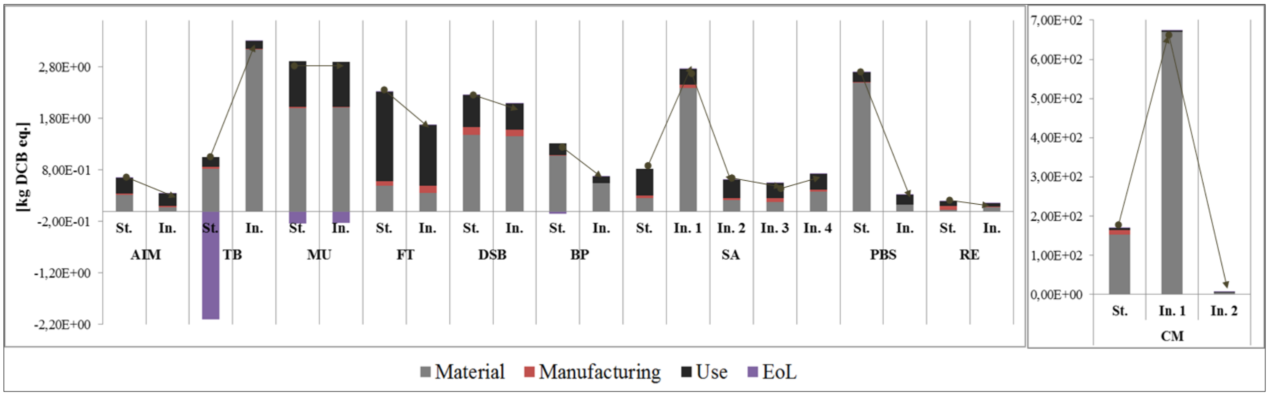
Figure 117 - Summary of FAETP indicator results.



10.1.7 HUMAN TOXICITY POTENTIAL (HTP$_{inf.}$)

HTP indicator results are summarized in Figure 118 below. As it shown, particular prevalence is given by the use of specific materials as aluminum (CM and SA1), but also for the use of synthetic material compared to natural (PBS) or to metals (TB) and the GF (BP). Another material, which plays a pejorative role, is the stainless steel (CM, MU). For that reason, the nature of the material composition should be accurately evaluated to reduce the toxicity factor.

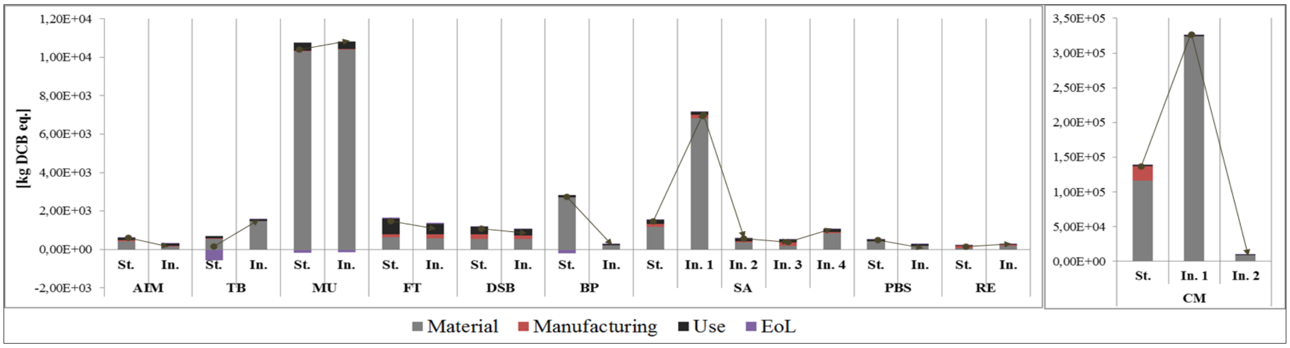
Figure 118 - Summary of HTP$_{inf.}$ indicator results.



10.1.8 MARINE AQUATIC ECOTOXICITY POTENTIAL (MAETP$_{inf.}$)

The negative effect of the use of aluminium is identified also on MAETP factor (CM, SA1). In addition, a negative effect is the employment of GF (BP). In addition to this the stainless steel (MU, CM, BP) bring a negative effect on MAETP indicator.

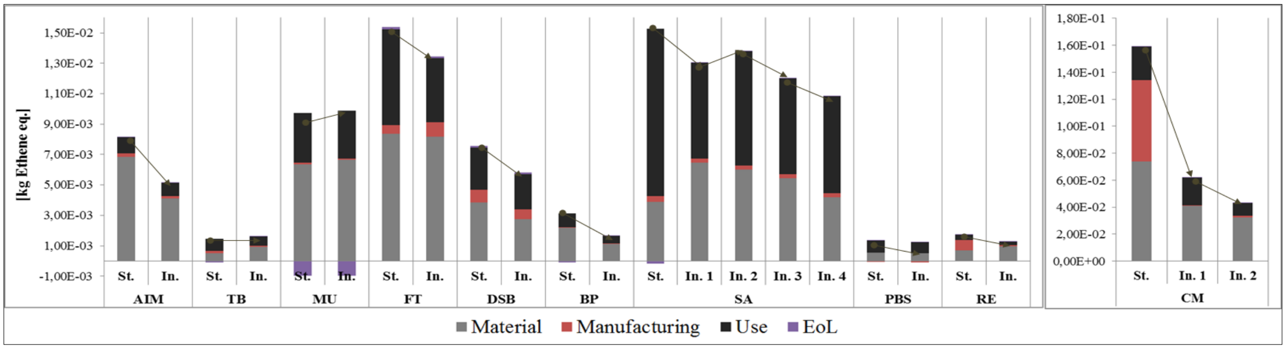
Figure 119 - Summary of MAETPinf. indicator results.



10.1.9 PHOTOCHEMICAL OZONE CREATION POTENTIAL (POCP)

The principal precursors of POCP generation are NOx, CO and volatile organic compounds, which are mostly, generated from exhausted tailpipe gases. For that reason component weight play a fundamental role in the reduction of this effect. Moreover, some materials as stainless steel (MU) produce harmful gases during their production, which contribute to the generation of POCP effect.

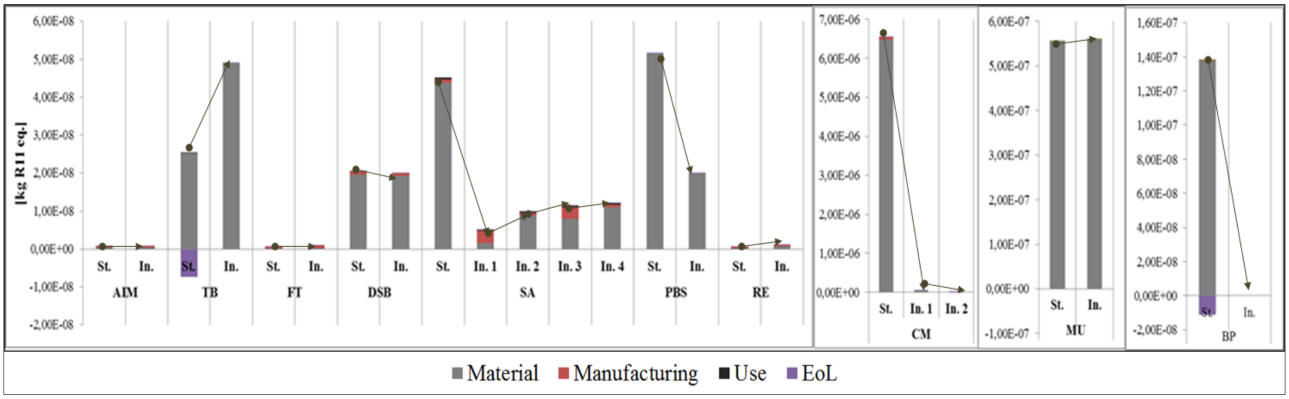
Figure 120 - Summary of POCP indicator results.



10.1.10 OZONE LAYER DEPLETION POTENTIAL (ODP steady state)

ODP effect is generated from trichlorofluoromethane substance, which in this case is generated from the steel production process especially for the stainless steel. That consideration is deduced from Figure 121, looking at CM, MU, SA and BP case studies results. Plastic production and aluminium has a minor contribution to the ODP effect.

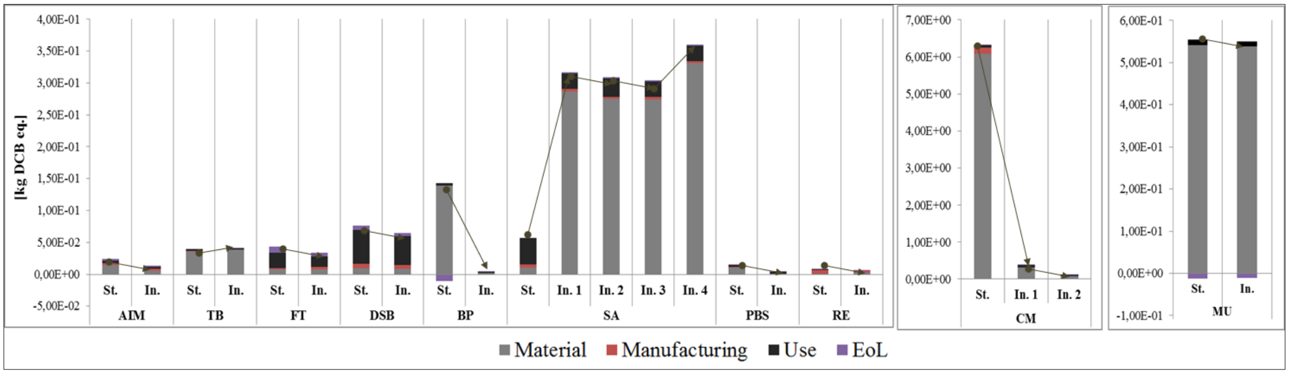
Figure 121 - Summary of ODP indicator results.



10.1.11 TERRESTRIC ECOTOXICITY POTENTIAL ($TETP_{inf.}$)

The production process of steel material influences the Terrestric Ecotoxicity effect. Those can be observed from the result displayed in Figure 122. In particular, different magnitude regards the CM and MU component for which a relevant amount of material is required.

Figure 122 - Summary of $TETPi_{nf}$ indicator results.

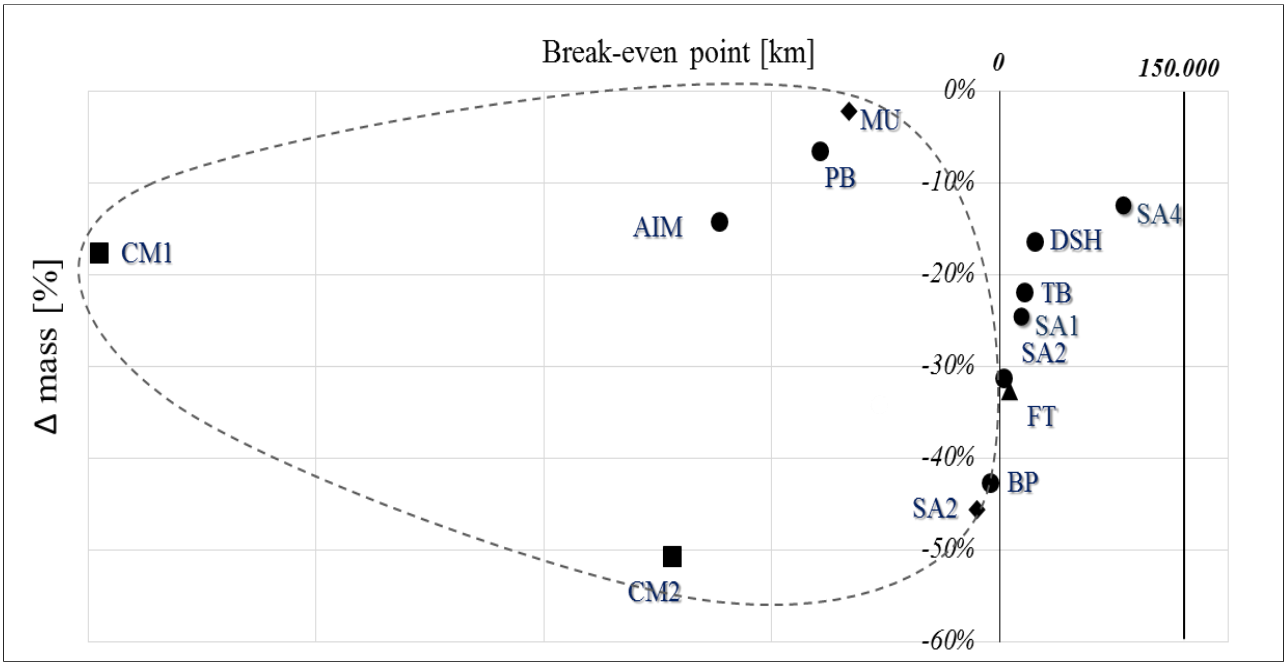


10.2 BREAK-EVEN POINTS GRAPH

In Figure 123 is displayed a synoptic of all the GHG emissions break-even points – occurred and not occurred – according to the delta mass decrease (%). The coordinates refer to the kilometers traveled by the vehicle in relation to the mass variation. The value of GHG emissions taken into consideration are reported for each case studies application in chapter 6 and 7. In this specific case the EoL internalization has been accounted consenting only the worst scenario option, Not all the component present a real break-even point, since the effective benefit on GWP impact decrease is perceived before vehicle use (thus component figure within the dotted circle before 0 km coordinate). To be specific, those components are CM1, CM2, AIM, PB, MU, SA2 and BP.

Although for other component, the lightweight advantage is perceived after a specific vehicle life span. The shortest pathway is verified for FT whereas just about 125.000 the SA4 occurs.

Figure 123 – Case studies break-even points



10.3 SENSITIVITY ANALYSIS

Following a full description on the sensitivity analysis is presented: firstly describing the EoL allocation recycling effect and as last the secondary effect observed during component use.

10.3.1 EOL MANAGEMENT

In the previous studies metal and non-metal recovery allocation has been set as a medium rate value with ASR processing selection between landfill (benchmark) and incineration (scenario 3).There are different policies of material recovery according to the type and composition but also the feasibility. These topics already discussed in the previous chapters are here taken with a perspective on components / pieces. First of all, the recovery of materials is a procedure that is certainly more advantageous than sending it to landfill, but it involves a waste of resources and is not really zero-impact. In the economy of the whole life cycle process, environmental conservation is certainly beneficial as the impact generated by the production of virgin material is much higher than that of the second raw material. The case of plastics is different, especially the composites for which the environmental advantage derives from the incineration of the same. Surely, the incineration process apparently does not benefit from the point of view of emissions generation (especially CO_2) because its own generation is inevitably linked to the process of energy recovery through incinerator. Hereafter is analyzed any possible repercussion due to the variation of different recycling rate (therefore, net of renovation and reuse / recovery activities carried out upstream of the plant. To be specific three different scenarios:

1. Scenario 1: metal and non-metal *low* recovery recycling allocation (12% steel and 20% non-metal) and ASR landfill;
2. Scenario 2: metal and non-metal *high* recovery recycling allocation (47% steel and 70% non-metal) and ASR landfill;
3. Scenario 3: metal and non-metal *medium* recovery recycling allocation (30% steel and 42% non-metal) and ASR incineration.

Considering that the recovery processes of the metal components that now have very high efficiencies, so as to be able to recycle almost completely these materials, unless you cannot mediate upstream of the shredding by promoting recovery processes pushed (potentially very burdensome), for respecting the European objectives will have to go through new ways of managing the car - fluff. The high calorific content of this refusal opens up interesting scenarios from the point of view of energy recovery.

In this regard, the GWP has been chosen as a representative indicator on the possible difference linked to the differences that are created between the various potential scenario options compared to a standard one. In general, these advantages derive from the recovery of metals that can be made available again for other uses as raw materials-second: among the main ones there are iron, aluminum and copper. The use of a second raw material, in fact, allows avoiding the impacts connected to the extraction, processing and transport of virgin raw materials. Indeed, even the whole of the activities that lead to the recovery of the second raw material has a not negligible environmental cost, which has been counted. However, all the activities that go from transporting ELVs and the second raw material to shredding and final disposal of waste, have environmental consequences that are decidedly more contained compared to the cycle of virgin raw materials. Obviously, however, there are margins, even significant, for improvement; considering that, the first item in terms of negative environmental impacts of the whole ELVs recovery chain is represented by transport. In order to have a comprehensive view the GWP indicator has been proposed so check the carbon footprint, with reference on benchmark and comparison among the various EoL scenarios. In particular Figure 124 (here is excluded CM2 due to its magnitude, the complete scattered graph is reported in annex F) is a reformulation of what presented in Figure 113, since present a synoptic portrait on the ΔGWP score for the components according to different EoL options correlated to their weight decrease. Each scattered points are referred to the GWP value for the specific component according to the different EoL options.

The contribution to the carbon footprint is given in particular by the saving of emissions connected to the extraction activities of raw materials and the steel production process. As can be seen from the synoptic framework, the EoL has a relevant influence on the variation of GWP effect, since for all the components is visible the shift from all the benchmark. In

Table 103 are provided data on the various deviations of the GWP indicator taking the benchmark as a reference. From the graph and more precisely from the values shown in the table the following comments can be drawn:

- *for the components made exclusively of plastics and/or plastic compounds* (AIM, FT, DSH, PBS, RE) no variation are registered for scenario 1 and 2 for components made of plastics; on the contrary when scenario 4 is assumed (the incineration) the GWP emissions increase.
- *For the component where the standard metal material (steel) is substituted with plastic (also partially)* (CM2, SA2, SA3), the selection of scenario 4 with incineration solution generate minor emissions; better performance are registered when higher recycling allocation rate is selected (scenario2). The most sensible variation regards the CM2 due to their material quantity. It has been observed that despite the scenario 2 has a lower quality rate than benchmark, the convenience related to the GWP saving during component use overcome this final effect.
- *For the component where the standard non-metal material (aluminum) is substituted with plastic (also partially)* (TB), the higher recycling rate represents the most favourable option for GHG savings (the scenario 1 is the pejorative).
- *For the component where the standard metal material (steel) is substituted with non-metal material aluminium (also with a few quantity of plastic)* (CM1[40]): the incineration process do not influence EoL performance due to the absent of plastic. Considering the recycling allocation, the higher the rate is and the more CO2 emissions are generated.

No sensible discrepancies are perceived for the component constituted with the same material with slight weight decrease (MU).

Overall the most discrepancy among benchmark and scenarios are observed for CM1, CM2 (due to the sensible weight incidence) and for the component constituted with plastic in the selection of incineration (scenario 4) option.

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[40] Graph reported in annex F.

Figure 124–Synoptic framework sensitivity GWP indicator behavior.

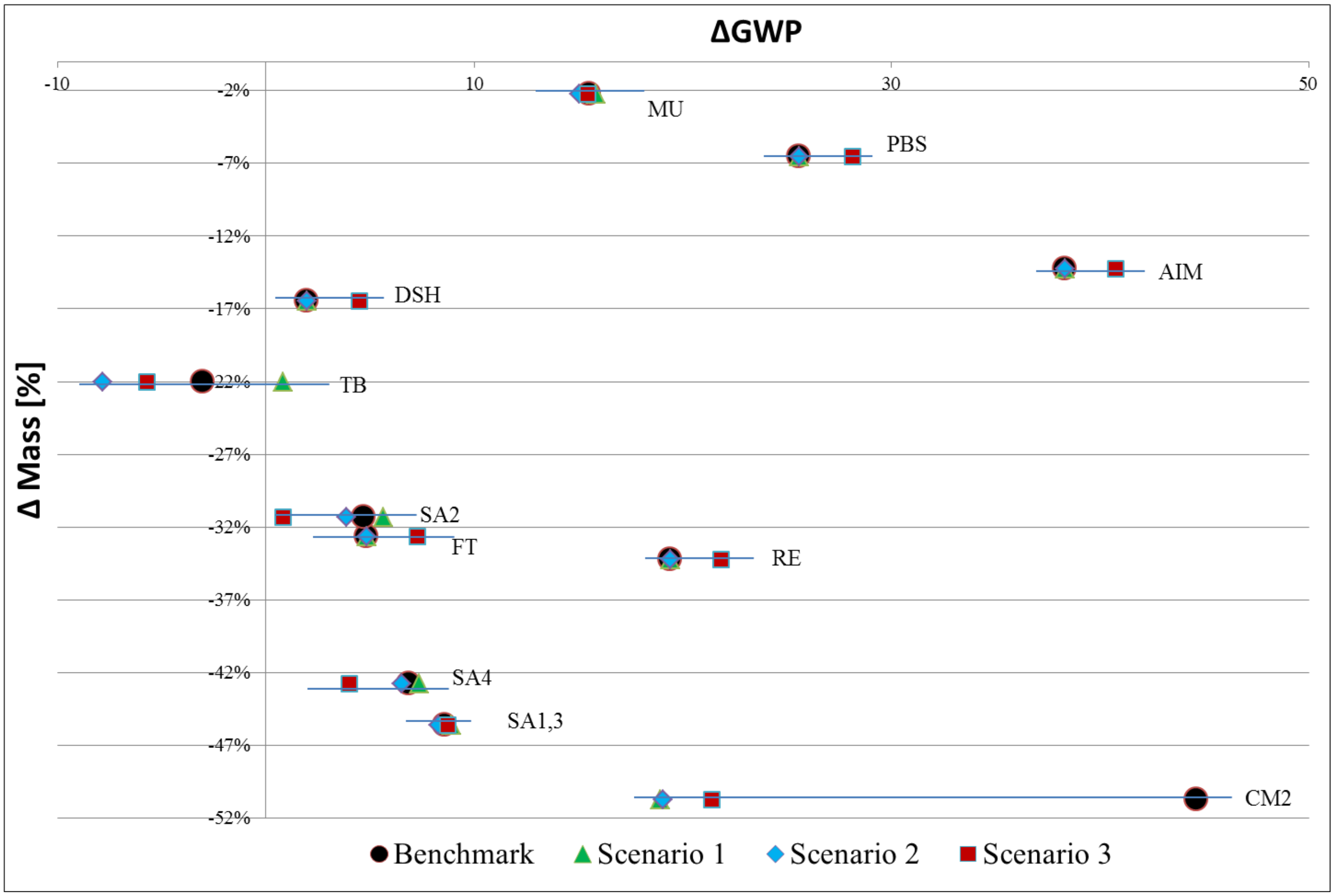


Table 103–Delta GWP of components with reference on benchmark.

Component name	Component weight	Δscenario1	Δscenario2	Δscenario3
AIM	-14%	0,0	0,0	-2,4
TB	-22%	-3,8	4,8	2,7
MU	-2%	-0,3	0,5	0,1
FT	-33%	0,0	0,0	-2,5
DSH	-16%	0,0	0,0	-2,5
PBS	-7%	0,0	0,0	-2,6
BP	-46%	-0,3	0,3	-0,1
CM1	-18%	6,8	-9,4	0,0
CM2	-51%	25,7	25,6	23,3
SA1,3	-31%	-0,9	0,9	3,9
SA2	-43%	-0,5	0,4	2,9
RE	-34%	0,0	0,0	-2,5

10.3.2 SECONDARY EFFECT

The increase of components weight inevitably involves an increase of the whole vehicle system linked to the body-in-white, suspension organs, drivetrain, and especially it is necessary to increase the size of the engine and the driving torque to maintain equivalent acceleration performance and functionality. This effect can be found in an empirical inverse manner if the weights are reduced; in particular, further weight savings due to a reduction in the main component weight is called "secondary effect"; which distinguishes itself precisely from the "primary" reduction of the initial component. The lighter vehicle is associated with lighter loads, less friction and drag and requires less power to be accelerated. It is important for the calculation of the benefit linked to the secondary effect, the weight ratio of the various masses of the different vehicle sub-systems depend on the total weight of the vehicle.

The secondary effect due to the attachment of the component is perceptible during the use phase, therefore for the sensitivity evaluation an inclusion was made starting from the reference FRV model. In fact, in the previous results only the effects due to the primary reduction were shown. To estimate the potential for secondary mass savings, it is important to differentiate the structural mass and the mass linked to the components, since only the mass of the subsystem that has a physical relationship with the total weight of the vehicle will be affected by lightning and therefore mass decomposing.

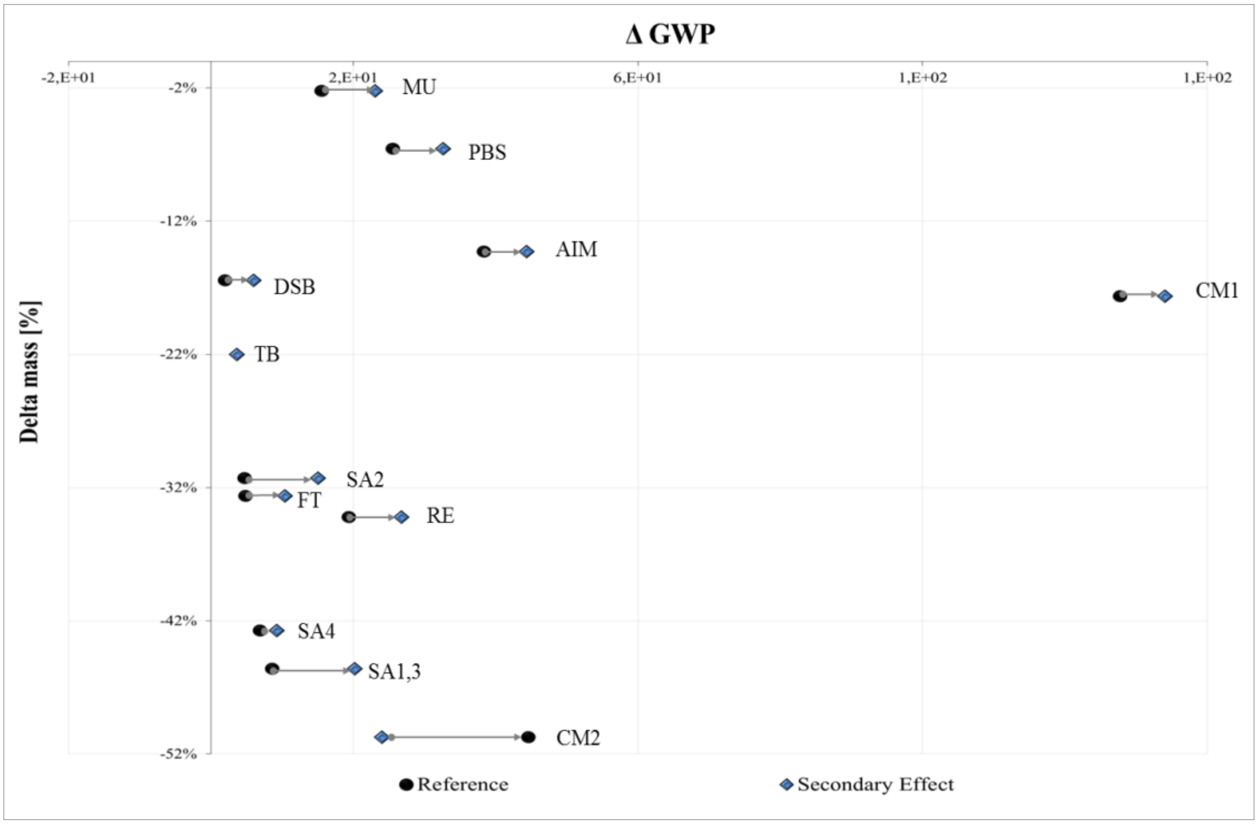
To include SE a re-formulation of FRV calculation is proposed according to formula 10 *(Raugei et al., 2015)* and 11*(Kelly et al., 2015).*

Gasoline: $FRV_{SE} = 0.001 \times Pmax + 0.198;$ *(10)*

Diesel: $FRV_{SE} = 0.0009 \times Pmax + 0.1721;$ *(11)*

Results of the calculation have been reported in Figure 125 considering GWP indicator as representative. From the scattered figure could be seen that inclusion of secondary effects, has a visible influence in the use stage modelling and affect the results in a significant mode. Indeed is affected by the powertrain features. Furthermore, it can be observed that the SE is influenced by mass percentage degree, but also for the mass incidence of the component within the vehicle selected. A consideration of the lightweighting sensitivity referred to vehicle weight has been previously reported in Figure 38.

Figure 125 – Secondary Effect due lightweighting on GWP.



10.3 CONCLUSION

In this chapter, a synoptic picture of all the results obtained have been presented. In particular, have been grouped the results obtained for each case study application according to a specific environmental indicator. The ultimate scope is to analyze any possible correlation among the environmental improvement strategy with the benefits results that it causes. Based on the results attained, the following considerations can be assumed and henceforward discussed.

First, the mass reduction strategy, promoted as a primary strategy by the automotive sector, does not always lead to positive results in the life cycle. Lightweight durable solutions that outperform metals: that is the future performance target in automotive marketMass reduction if very significant undoubtedly implicates substantial benefits especially if secondary effect are considered. Surely, the primary benefit linked to mass reduction is linked to the reduction of impact linked to the use phase of the component, if the only incident factor to the component use is correlated to its mass. In fact, other considerations should be taken into account when modeling component use. For instance the operation of electronic component both consider mass factor and energy consumption, this is the case study analyzed regard in auxiliary module where the heaviest component was the one which absorbed less energy and resulted the best solution to the end.

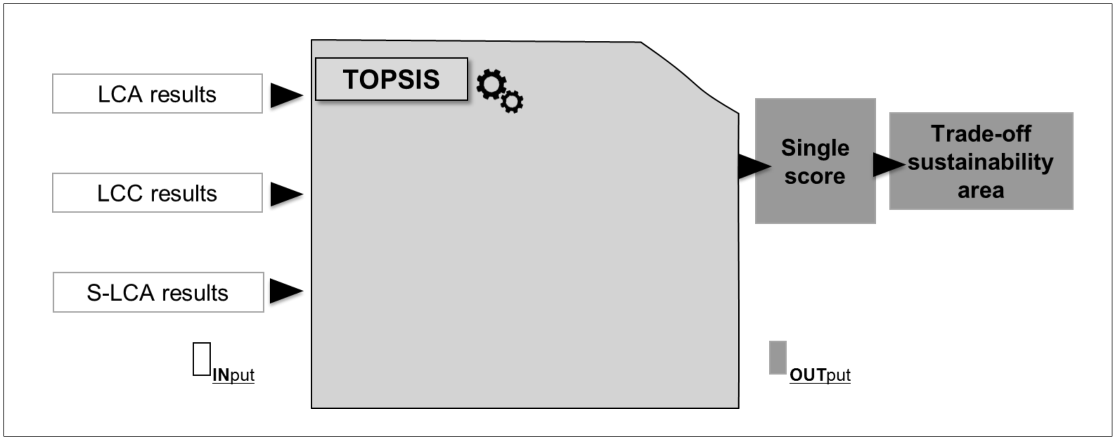
The selection of the best solution is far from simple, since must take into account a series of factors and elements that come into play. Surely, where the innovative solution brings benefits on all fronts, this difficulty does not arise. On the contrary, some innovative solutions offer advantages if we consider some phases of the life cycle and / or some phases of the life cycle. For instance, considering the example of plastics replacing metals: these lightweight materials certainly offer an advantage due to their lightness but worsen the effects on the incidence of their production and disposal.Replacing metals with a lightweight polymeric solution often equates to major efficiency improvements.

In view of the life cycle phase's contribution, results confirm that an automotive product generates more impacts for the segments linked to the extraction and processing of raw materials and use. For this reason, it is better to concentrate the reduction efforts on the impact generated by the selection and processing of materials and component weight rather than logistic and materials recovery implication. Another factor concerns the contrasting results on the various impact categories, it has been observed that the selection of an environmental improvement strategy brings benefit for some environmental issue and worsen the effect on the others.Engineers are constantly pressured to maximise performance whilst minimising component size and weight.There are numerous decisional variables to be put into play and the difficulty increases if additional factors are considered as economic and social variables. For this purpose, it may be useful to adopt tools that consider a customized calculation method for the company that makes the results as unbiased as possible. The ultimate purpose is to provide usable decisional variables, which can be used as drivers for the selection of the best sustainable option among different design alternatives. A possible way is to use Multicriteria Decision Making Tool as to rank various design alternatives, which integrate environmental, social and economic attribution.

11. PILOT PROJECT

A pilot project has been settled with the aim of integrating the 3 impact methods (LCA, eLCC and S-LCA) so far disjointed. The proposed framework (Figure 126) is thought to the purpose of giving a practical decision-making platform when deciding which design alternative to promote given each environmental, social, and economic impacts respectively. The Intuitionistic Fuzzy Multi-Criteria Decision Making and Technique for Order Preference by Similarity to Ideal Solution methods are then utilized to rank the life cycle sustainability performance of alternative automotive product design solutions. The essential goal of the TOPSIS *(Onat, N.C. et al., 2016)* approach is that the most preferred alternative should have not only the shortest distance from the positive ideal solution, but also the farthest distance from the negative ideal solution. One of the advantages of the TOPSIS method is that it provides effective results for the ranking of alternatives that have absolute data for each indicator.

Figure 126- Ranking design alternatives framework.



Decisions on alternatives sustainable products require a futuristic vision that includes the impacts generated on the environmental, economic and social sphere. At times, the performance of a product presents conflicting results between environmental, economic and social impacts, and in addition become contradictory objectives in the decision-making process. The objective of this chapter is to offer a possible approach to integrate the impact methodologies (LCA, LCC and S-LCA), trying to obtain a single impact score that encompasses the three sustainability dimensions. This goal is important in order to be able to effectively make comparisons between different solutions in a rational and efficient manner. In chapter 3, the difficulties related to the possible methodologies' integration have already been discussed. Surely there are several elements that make difficult to compare the different impact results: the different dimensions evaluate that make difficult to make comparison, the importance attributed to each criteria from the various decision makers (company members, users…). Decision makers' preferences are typically expressed in terms of weights assigned to the evaluation criteria.

The criteria are the basis on which the decision makers evaluate the alternatives. Therefor the various alternative are evaluated and ordered according to the importance (weight) assigned to the various criteria. A pattern to implement the decision-making process model is the multi-criteria analysis (MCMD).

MCDM methods are multiple criteria comparison procedures, which try to rationalize the decision-making process by optimizing a vector of several criteria, weighed according to the priorities (chosen by the decision maker/s). The criteria represent the different aspects on which to evaluate the different possibilities to choose from. The various criteria are often conflictual, compared to an alternative, the hierarchy decision process offer a compromise solution between the alternatives. Based on the performance of the alternatives with respect to the criteria considered and because of the weights that the decision-makers assign to the criteria, the various alternatives are evaluated and ordered. At the base of many MCDM methods, there is the need to add to each criterion a weight that is a measure of the importance that the decision maker expresses on each criterion, which will allow to draw a ranking of the importance among the different criteria, which will influence the alternatives. In this sense, the Multi-Criteria Decision Making (MCDM) analysis becomes an approach able to overcome the problems associated with such decision-making compromises on various alternatives.

There are several MCDM models widespread adopted in decision-making problems, including the Technique for Preference Order by Similarity to Ideal Solutions (TOPSIS).

The goal of the TOPSIS method is to sort the various alternatives according to a precise logic: the best alternative is the one that presents the shortest distance from the ideal positive solution and at the same time the farthest distance from the ideal negative solution. The TOPSIS method in this way offers the advantage of sorting according to this logic the various alternatives in a ranking of preference. The TOPSIS method is widely used to provide effective results for the classification of alternatives, despite that few case studies application on the LCSA topic are available.

11.1 CALCULATION METHOD

The purpose of the novel method proposed is to develop a comprehensive MCDM framework to compare different automotive design solutions based on their positive and negative social, economic, and environmental impacts. The flowchart reported is developed in order to integrate the TOPSIS methodology and validate a novel impact assessment framework. This procedure offers a life-cycle sustainability assessment model to compare different design solutions following LCA, LCC and S-LCA.

The information is shared according to an "input-output" logic among the various steps. Once obtained, information are elaborated starting from inventory to obtain one single impact score for each design solution. Below is presented the main step to implement TOPSIS methodology.

The implementation of the methodology consists of the following steps:
1) creation of a decision matrix [D] and weight vector= $[r_{ij}]_{nxm}$.

The decision matrix is a rectangular matrix of order *nxm*, where:*n* are the alternatives and *m* are the criteria. The generic element a_{ij} expresses the performance of the alternative i against criterion.

11.1.1 CRITERIA SELECTION

For this first pilot project case, the choice of criteria was based on the following characteristicsthat these must meet in order to guarantee:

- *Comprehensibility*, as to be an easily governable and understandable tool and above all avoid any kind of wrong or tendentious interpretation.
- *Significant*, to support decision making by identifying opportunities for improvement.
- *Compensivity*, to cover all the main aspects and significant impacts.
- *Manageability and comparability*, to monitor the evolution of results over time. In addition, some indicators (such as GWP) are developed in accordance with standards and offer the possibility of a continuous benchmark compared to the sector and competitors.
- *Controllability*, as the ability to maneuver this indicator and modify it according to the actions taken at a strategic and tactical level (DfA, DfE) so as to effectively track changes in performance.
- *Continuity*, as the indicator must be continually updated and monitored to track changes in performance.
- *Representativeness* of the sustainability dimensions considered.

2) Normalization of the matrix through the dimensionless scale of the values of the aij matrix, according to the relation:

$$r_{ij} = \frac{a_{ij}}{\sqrt{\sum_{k=1}^{n} a^2{}_{kj}}} \qquad (12)$$

11.1.2 WEIGHTING FACTORS: SELECTION METHOD

The weighted criteria have been selected considering Saaty method*(Saaty R.W., 1987).* In particular, the fundamental scale of relative importance (Table 104) has been used as a metric to develop the matrix of binary comparisons between the criteria (Table 105).

Table 104 - Fundamental Scale of Relative Importance (Saaty).

Intensity of Importance	Definition	Explanation
1	Equal importance	Indifferent
2	Weak or slight	
3	Weak Importance	Slightly better
4	Moderate plus	
5	Strong Importance	Better
6	Strong plus	
7	Very Strong Importance	Much Better
8	Very, very Strong	
9	Absolute Importance	DefinitelyMuch Better
1/2; …; 1/9	Reciprocals of above	A logical assumption

Table 105 - Matrix of weighed criteria.

	LCC	**E-LCA**			**S-LCA**		
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**
C1	1	2	2	2	2	2	2
C2	1/2	1	2	2	2	2	2
C3	1/2	1/2	1	2	2	2	2
C4	1/2	1/2	1/2	1	2	2	2
C5	1/2	1/2	1/2	1/2	1	2	2
C6	1/2	1/2	1/2	1/2	1/2	1	2
C7	1/2	1/2	1/2	1/2	1/2	1/2	1

The important criticality of this method is linked to the subjectivity of the weighted criteria matrix. In order to assess its robustness, Saaty *(Saaty R.W., 1987)*proposes the calculation of the consistency index, which must be less than 10%. Considering the matrix of weighted criteria in Table 105.

The Consistency Ratio (CR) proposed by Saaty (1977) is necessary to estimate the consistency of pairwise comparison matrix. It is calculated as reported in formula 13.

$$CR = \frac{CI}{IR} \tag{13}$$

Where:

- CI is the Consistency Index;
- RI is the Index Random.

The consistency Index (CU) is calculated using the formula (14)

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{14}$$

Where:

- $\lambda_{\max}$ is the maximum eigenvalue;
- n is the number of criteria.

The maximum eingevalue(l_{max}) is obteined mulplying the priority matrix [x] with pairwise comparison matrix [A] using formula 15.

$$A = [a_{ij}] = \begin{vmatrix} a_{11} & a_{12} & a_{13} & \cdots & a_{1m} \\ a_{21} & a_{22} & a_{23} & \cdots & a_{2m} \\ a_{31} & a_{32} & a_{33} & \cdots & a_{3m} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & a_{n3} & \cdots & a_{nm} \end{vmatrix} \times \begin{vmatrix} x_1 \\ x_2 \\ x_3 \\ \cdots \\ x_n \end{vmatrix} = \begin{vmatrix} y_1 \\ y_2 \\ y_3 \\ \cdots \\ y_n \end{vmatrix} \tag{15}$$

In particular,the elements *yi* are obtained by the sum of product between the elements of the two matrixes (formula 16).

$$\begin{aligned} y_1 &= a_{11} \cdot x_1 + a_{12} \cdot x_2 + a_{13} \cdot x_3 + \ldots + a_{1m} \cdot x_n \\ y_2 &= a_{21} \cdot x_1 + a_{22} \cdot x_2 + a_{23} \cdot x_3 + \ldots + a_{2m} \cdot x_n \\ y_3 &= a_{31} \cdot x_1 + a_{32} \cdot x_2 + a_{33} \cdot x_3 + \ldots + a_{3m} \cdot x_n \\ &\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ y_n &= a_{n1} \cdot x_1 + a_{n2} \cdot x_2 + a_{n3} \cdot x_3 + \ldots + a_{nm} \cdot x_n \end{aligned} \tag{16}$$

The elements *xi* of priority matrix are obtained by the averaging (*arithmetic*) of rows of matrix [A]. Dividing the components *y1* of vector y by the homologous of vector *x (xi)* we obtain the components zi (*z*).

λ_{max} (formula 17)is obtained by the mean of z_i components (formula 18).

$$\lambda_{max} = \frac{(z_1 + z_2 + z_3 + \ldots + z_n)}{n} \qquad (17)$$

$$\begin{aligned} z_1 &= y_1 / x_1 \\ z_2 &= y_2 / x_2 \\ z_3 &= y_3 / x_3 \\ \ldots\ldots\ldots\ldots &\quad \ldots\ldots\ldots \\ z_n &= y_n / x_n \end{aligned} \qquad (18)$$

If $CR(A) \leq 0.1$, the pairwise comparison matrix is considered to be consistent enough. In the case $CR(A) \geq 0.1$, the comparison matrix should be improved. The value of RI depends on the number of criteria being compared.

b. The Index Random (IR) is generated randomly Table 106.

Table 106 - IR values for different number of criteria (n).

n	IR
1	0
2	0
3	0,58
4	0,90
5	1,12
6	1,24
7	1,32
8	1,41
9	1,45
10	1,49
11	1,51
12	1,48

11.1.3 NORMALIZATION AND WEIGHTENING

3) Subsequently, the weighted decision matrix obtained is obtained by multiplying the matrix R by the weight vector, thus obtaining the matrix V.

$$v_{ij} = w_j x r_{ij} \qquad (19)$$

11.1.4 ALTERNATIVES RANKING

4) Then the two virtual solutions **A**$^+$ ideal positive and **A**$^-$ negative ideal, which are obtained from the [V] matrix are defined according to the two following relationships:

$$A^+ = \{maxv_{ij}\ con\ J \in J_b;\ minv_{ij}\ J \in J_c\}\ per\ i=1,2,\dots\dots n; \qquad (20)$$

$$A^- = \{minv_{ij}\ con\ J \in J_b;\ minv_{ij} J \in J_c\}\ per\ i=1,2,\dots\dots n.(21)$$

In which, with J_b, the benefit criteria are indicated and the cost criteria are indicated with J_c.

5) Later, considering the alternatives as points of a space with *m* dimensions (*m* number of criteria), the distances between the real alternatives and the virtual ones have to be calculated. The generic *j-mo* axis is indicative of the normalized and weighted performance v_{ij} of the alternative considered with respect to criterion C_j.The distance is calculated with two following relationships:

$$S_{i+} = \sqrt{\sum_1^m j(v_{ij} - v_{j+})^2}\ per\ i= 1,2,\dots..n. \qquad (22)$$

$$S_{i-} = \sqrt{\sum_1^m j(v_{ij} - v_{j-})^2}\ per\ i= 1,2,\dots..n. \qquad (23)$$

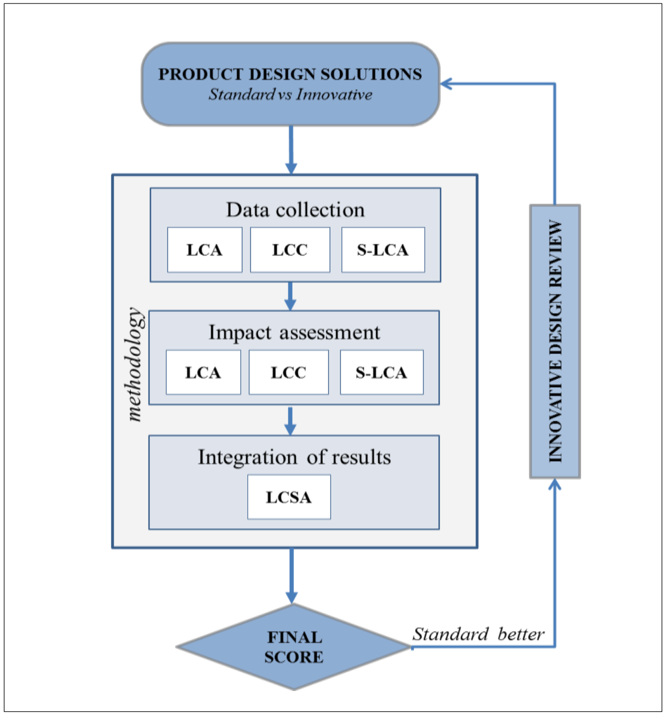
6) At this point, the relative distances of the alternatives are determined from the ideal solution of the decision problem by means of the following ratio:

$$C_{i+} = \frac{S_{i-}}{S_{i-} + S_{i+}} \qquad (24)$$

7) To conclude the C_{i+} alternatives are ranked.

The ideal solution is the one that presents at the same time the minimum distance from A^+ and the maximum from A^-. The workflow to use as to develop the calculation model is depicted in Figure 127.

Figure 127 - Ranking design alternatives framework.



11.2 CASE STUDY APLLICATION: AUTOMOTIVE DASHBOARD PANEL

In order to validate the new sustainability impact framework, a first application was made for the project linked to the innovative design of the dashboard. In particular, the methodology has been applied to determine the best sustainable solution between a standard and innovative dashboard, during the initial design phase. In particular, an Intuitionist Fuzzy Set method is used to define the weights of each of the indicators presented. The solution ranking is determined using TOPSIS method.

The main focus of this study is to develop a comprehensive MCDM framework to compare and rank these vehicle types based on their positive and negative social, economic, and environmental impacts. Next, a TOPSIS-based decision making analysis is developed to rank the alternative vehicle technologies.

There is no comprehensive study of LCA, LCC and S-LCA indicators, but only those selected as representative for the automotive sector are selected as criteria in the decision matrix. To compile the criteria column in the decision matrix, the TOPSIS method will be used, which will provide, at the end of its application, a ranking according to the distance that each alternative has towards the best and worst virtual alternatives, and will therefore be precisely the index Ci *, which represents the final result of the method, to constitute the searched column. The dashboard case study has been presented in CHAPTER 7 SECTION 2. Here is discussed the final TOPSIS implementation stage. Seven representative criteria have been selected and reported in Table 107.

Table 107 - Criteria selection.

DIMENSION	CRITERIA	UNIT
ECONOMIC	C1 [production; use; EoL costs]	€
ENVIRONMENTAL	C2 [GWP]	kg CO2-eq.
	C3 [ADPel.]	kg Sb-eq.
	C4 [PED]	MJ
SOCIAL	C5 [Health & safety training]	Hours
	C6 [Incidents during the reporting period]	Number
	C7 [Workers fairy salary]	Percentage

Subsequently the creation of the normalized decision matrix and the selection of the weight factor has been accomplished.

Table 108 – Decision matrix.

	LCC	E-LCA			S-LCA		
D	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**
P1 [Standard design]	1,81E+01	1,50E+01	3,26E-05	4,75E+02	1,18E+00	4,60E-01	1,00E+02
P2 [Innovative design]	1,67E+01	1,66E+01	6,32E-05	5,44E+02	1,18E+00	4,60E-01	1,00E+02

The normalized matrix has been obtained using formula 18 and the weighted normalized decision matrix using Saaty method, which resulted in what reported in Table 109. Normalized matrix is presented in Table 110and weighted matrix in Table 111.

Table 109 -Criteria weight (wC).

wC1	0,24	24,35%
wC2	0,20	19,98%
wC3	0,16	16,39%
wC4	0,12	11,79%
wC5	0,11	11,03%
wC6	0,09	9,05%
wC7	0,07	7,42%

Table 110 – Normalized matrix.

[Rij]	C1	C2	C3	C4	C5	C6	C7
P1 [Standard design]	7,36E-01	6,70E-01	4,58E-01	6,58E-01	7,07E-01	7,07E-01	7,07E-01
P2 [Innovative design]	6,77E-01	7,42E-01	8,89E-01	7,53E-01	7,07E-01	7,07E-01	7,07E-01

Table 111 - Weighted normalized decision matrix.

[Vij]	C1	C2	C3	C4	C5	C6	C7
P1 [Standard design]	1,79E-01	1,34E-01	7,51E-02	7,76E-02	7,80E-02	6,40E-02	5,25E-02
P2 [Innovative design]	1,65E-01	1,48E-01	1,46E-01	8,88E-02	7,80E-02	6,40E-02	5,25E-02

The positive ideal (A^+) and negative ideal solution (A^-) are calculated (based on formula 19 and 20) and reported in Table 112. The separation measures (Si) of each alternative from positive ideal (Si+) and negative ideal solution (Si**-**) are calculated using formula 21 and 22 and reported in Table 113.

Table 112 - The positive ideal (A+) and negative ideal solution (A-).

	C1	C2	C3	C4	C5	C6	C7
A+	1,65E-01	1,34E-01	7,51E-02	7,76E-02	7,80E-02	6,40E-02	5,25E-02
A-	1,79E-01	1,48E-01	1,46E-01	8,88E-02	7,80E-02	6,40E-02	5,25E-02

Table 113 – Positive and negative separation measures.

	C1	C2	C3	C4	C5	C6	C7	S_i^+ (*)
P1 [Standard design]	2,08E-04	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	1,44E-02
P2 [Innovative design]	0,00E+00	2,08E-04	4,98E-03	1,27E-04	0,00E+00	0,00E+00	0,00E+00	7,29E-02
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**S_i^- (*)**
P1 [Standard design]	0,00E+00	2,08E-04	4,98E-03	1,27E-04	0,00E+00	0,00E+00	0,00E+00	7,29E-02
P2 [Innovative design]	2,08E-04	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	1,44E-02

Finally have been calculated (formula 24) the relative closeness to the ideal solution (Ci^+) (Table 114) and consequently the rank preference order (**C_i^+ max)** is defined(Table 115).

Table 114 – Ideal solution.

C_i^+	
P1 [Standard design]	8,35E-01
P2 [Innovative design]	1,65E-01

Table 115 – Rank preference order.

		Preference Order
P1 [innovative design]	0,18	1
P2 [standard design]	0,16	2

Lastly, the calculation of the consistency (CR) ratio is calculate using formula 14 and the eigenvalue value based on formula 15,16, 17 and 18, which are reported in Table 116.

Table 116Eigenvalue value calculation.

x_1	1,81	y_1	13,07	z_1	7,21	λ_{max}	7,29
x_2	1,49	y_2	10,68	z_2	7,18		
x_3	1,22	y_3	8,71	z_3	7,15		
x_4	0,88	y_4	6,78	z_4	7,73		
x_5	0,82	y_5	5,97	z_5	7,27		
x_6	0,67	y_6	4,88	z_6	7,26		
x_7	0,55	y_7	4,00	z_7	7,24		
TOT	**7,44**						

Base on the results of table X the Consistency Index IC and Random Index IR are calculated as follows:

$$IC = \frac{\lambda_{max} - n}{n - 1} = \frac{0,29}{6} = 0,05$$

$$IR = 1,32 \quad (\text{for} \quad n = 7)$$

Consequently, the CR resulted in a value minor that 10% which is a reasonable and acceptable solution.

CR= 3,7 % < 10%.

11.3 CONCLUSION

In the present chapter a multi-criteria analysis has been developed in order to calculate a single score solution, as to find a method to balance among , sometimes conflicting, diverse criteria. In particular, the different criteria selected are base on the three sustainability bottom-lines dimensions, with the purpose to obtain a single impact score that balance among environmental and socioeconomic objectives. Results demonstrate that the application of the novel method offers the possibility to obtain the trade-off relationships among the three dimensions. Moreover the present method offers the possibility to move toward a more tailored and customized method, which is based on a impact-weighted criteria selected by the Company decisions.

In light of the positive results achieved, the company could move toward and integrative approach, which take into account Multi-criteria Decision Making tool, trying to customize selection of criteria and weight base on company expert decisions. In particular, TOPSIS tool is an instrument, which balance among different impact scenarios trade-off offering a single measurable impact score and guide the offering of encouragements to the right domains for sustainable transportation. Nevertheless, it is important to bear in mind the subjectivity of the method linked to the selection of the criteria and weight. Different weighting scenarios could be applied to account for variability in a decision- maker's priorities, such as giving less weight to socio economic indicators and more weight to environmental indicators.

In the next future possible steps could regard the construction of a more customized method based on the selection of criteria and weight base on expert decision. The investigation could be accomplished via survey and questioning to the major expert (as R&D board) and with stakeholder as to involve an external opinion; in order to make an equal trade-off among internal and external necessities.

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ANNEXES

ANNEX A – TERMS AND DEFINITIONS

Allocation

Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems (ISO 14044, 2006).

ASR

Automotive Shredded residue represents the remaining fraction of End of Life Vehicle treatment.

Battery electric vehicles (BEV)

Vehicle in which motion is caused by an electric motor and the energy used for moving the vehicle is stored in a battery.

Characterization factor

Factor derived from a characterization model which is applied to convert an assigned life cycle inventory analysis result to the common unit of the category indicator.

NOTE: the common unit allows calculation of the category indicator result.

Comparative assertion

Environmental claim regarding the superiority or equivalence of one product versus a competing product that performs the same function.

“Cradle to grave” approach

A “cradle→ to → grave” assessment considers impacts at each stage of a product’s life cycle, from the time natural resources are extracted from the ground and processed through each subsequent stage of manufacturing, transportation, product use, recycling, and ultimately, disposal.

Critical review

Process intended to ensure consistency between a life cycle assessment and the principles and requirements of the International Standards on life cycle assessment.

NOTE 1: the principles are described in ISO 14040:2006, 4.1.

NOTE 2: the requirements are described in this International Standard.

Data quality

Characteristics of data that relate to their ability to satisfy stated requirements.

Elementary flow

Material or energy entering the system being studied that has been drawn from the environment without previous human transformation, or material or energy leaving the system being studied that is released into the environment without subsequent human transformation (ISO 14044, 2006).

Environmental aspect

Element of an organization's activities, products or services that can interact with the environment.

Functional unit

Quantified performance of a product system for use as a reference unit (ISO 14044, 2006).

Hybrid vehicles

Vehicles in which an electric motor supplies at least part of the propulsion while at least part of the energy to propel the vehicle and/or to drive the electric motor is supplied by an internal combustion engine.

Impact category

Class representing environmental issues of concern to which life cycle inventory analysis results may be assigned (ISO 14044, 2006).

Incineration

Is a waste treatment process that involves the combustion of organic substances contained in waste materials, through which can be converted the waste into ash, flue gas, and heat.

Interested party

Individual or group concerned with or affected by the environmental performance of a product system, or by the results of the life cycle assessment.

International Reference Life Cycle Data System (ILCD)

The ISO 14040 and 14044 standards provide an indispensable framework for Life Cycle Assessment (LCA). This framework, however, leaves the individual practitioner with a range of choices, which can strongly affect the final results in an assessment. While flexibility is essential in responding to the large variety of questions addressed, further guidance is needed to support consistency and quality assurance. The International Reference Life Cycle Data System has therefore been developed to provide guidance for consistent and quality assured Life Cycle Assessment data and studies. The ILCD consists primarily of the ILCD Handbook and the ILCD Data Network. The development of the ILCD was initiated by the European Commission and has been carried out through a broad international consultation process with experts, stakeholders, and the public.

Input

Product, material or energy flow that enters a unit process.

NOTE: products and materials include raw materials, intermediate products and co-products.

Life cycle

Consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal (ISO 14044, 2006).

Life Cycle Assessment (LCA)

Life Cycle Assessment is a methodology based on the compilation of the inputs and outputs and the evaluation of the potential environmental impacts of a product system throughout its life cycle (ISO 14044, 2006). LCA is based on a functional perspective and encompasses four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation. Moreover, this method is of an iterative nature since insight gained from the interpretation phase can typically be used to optimize specific issues in the other phases. Repeating this procedure several times can improve the quality of the results.

Life cycle impact assessment (LCIA)

Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product (ISO 14044, 2006).

Life cycle inventory analysis (LCI)

Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle (ISO 14044, 2006).

Life cycle inventory analysis result (LCI) result

Outcome of a life cycle inventory analysis that catalogues the flows crossing the system boundary and provides the starting point for life cycle impact assessment (ISO 14044, 2006).

Life cycle interpretation

Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations.

Life cycle inventory analysis result (LCI result)

Outcome of a life cycle inventory analysis that catalogues the flows crossing the system boundary and provides the starting point for life cycle impact assessment (ISO 14044, 2006).

Output

Product, material or energy flow that leaves a unit process.

NOTE: products and materials include raw materials, intermediate products, co-products, and releases.

Process

Set of interrelated or interacting activities that transform inputs into outputs (ISO 14044, 2006).

Product

Any goods or service (ISO 14044, 2006).

NOTE: the product can be categorized as follows:

- Services (e.g. transport);
- Software (e.g. computer program, dictionary);
- Hardware (e.g. engine mechanical part);
- Processed materials (e.g. lubricant);
- Services have tangible and intangible elements. Provision of a service can involve, for example, the following:
- An activity performed on a customer-supplied tangible product (e.g. automobile to be repaired);
- An activity performed on a customer-supplied intangible product (e.g. the income statement needed to prepare a tax
- return);
- The delivery of an intangible product (e.g. the delivery of information in the context of knowledge transmission);

- The creation of ambience for the customer (e.g. in hotels and restaurants).
- Software consists of information, is generally intangible, and can be in the form of approaches, transactions or procedures. Hardware is generally tangible and its amount is a countable characteristic. Processed materials are generally tangible and their amount is a continuous characteristic.

Raw material

Primary or secondary material that is used to produce a product (ISO 14044, 2006).

NOTE: secondary material includes recycled material.

Recycling

Reprocessing in a production process of the waste materials for the original purpose or for other purposes, excluding processing as a means of generation energy.

Recovery

Reprocessing in a production process of the waste materials for the original purpose or for other purposes, together with processing as a means of generation energy.

Reference flow

Measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit (ISO 14044, 2006).

Renewable energy

Any energy resource that is virtually inexhaustible, naturally regenerated over a short time scale and derived directly from the sun (such as thermal, photochemical, and photoelectric), indirectly from the sun (such as wind, natural hydropower (i.e. not from pumped storage), and photosynthetic energy stored in renewable biomass), or from other natural movements and mechanisms of the environment (such as geothermal and tidal energy). Renewable energy does not include energy resources derived from fossil fuels, waste products from fossil sources, or waste products from inorganic sources.

Re–use

Any operation by which component parts of end-of-life vehicles are used for the same purpose for which they were conceived.

Substitution

Solving multifunctionality of processes and products by expanding the system boundaries and substituting all not required functions with alternatives, i.e. with process(es) or product(s) that supersede the not required functions. Effectively, the life cycle inventory(ies) of the superseded process(es) or product(s) is subtracted from that of the analyses system, i.e. the system is 'credited'. Substitution is a special (subtractive) case of applying the system expansion principle.

System

Any good, service, event, basket-of-products, average consumption of a citizen, or similar object that is analyzed in the context of the LCA study.

Note that ISO 14044, 2006 generally refers to "product system", while broader systems than single products can be analyses in an LCA study; hence here the term "system" is used. In many but not all cases, the term will hence refer to products, depending on the specific study object. Moreover, as LCI studies can be restricted to a single unit process as part of a system, in this document the study object is also identified in a general way as "process/system" (ILCD, 2010).

System boundary

Set of criteria specifying which unit processes are part of a product system.

NOTE: the term “system boundary” is not used in this International Standard in relation to LCIA.

Unit process

Smallest element considered in the life cycle inventory analysis for which input and output data are quantified (ISO 14044, 2006).

Vehicle mass (mV)

Represent the complete vehicle shipping mass, as specified in ISO 1176, plus the mass of lubricants, coolant (if needed), washer fluid, fuel, spare wheel(s), fire extinguisher(s), standard spare parts, chocks, standard tool-kit.

Waste

Substances or objects which the holder intends or is required to dispose of.

NOTE: the definition is taken from the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal (22 March 1989) but is not confined in this International Standard to hazardous waste.

ANNEX B – MODELING NOVEL MATERIALS PROFILE

This section displays the modeling of the materials profile within Gabi software, with a reference quantity for each of 1 kilogram. The lists of all the novel materials modeled for MM use are described in CHAPTER 5.

B.1 METALS

Figure B.1 – Stainless steel [AISI 301] including stamping and bending process as modeled within Gabi software.

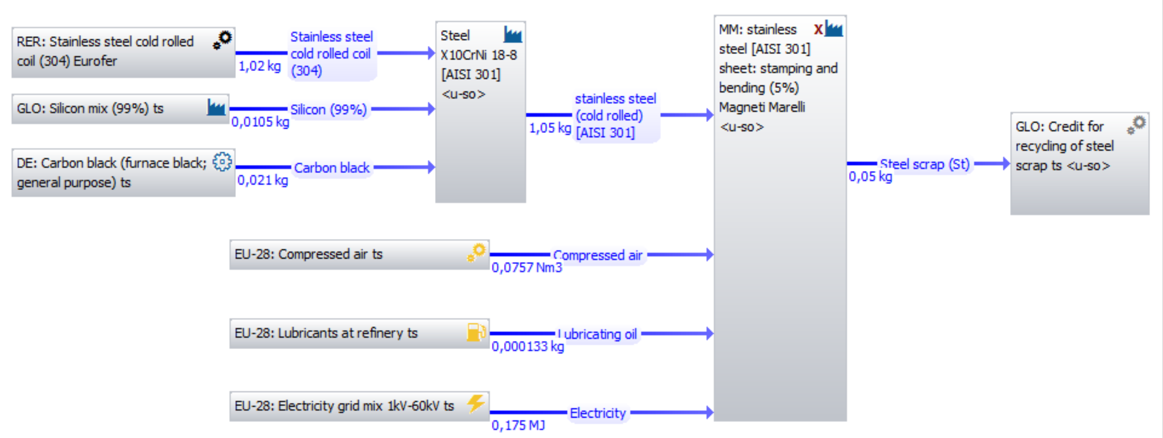


Figure B.2 - Stainless steel [AISI 430] flat product as modeled within Gabi software.

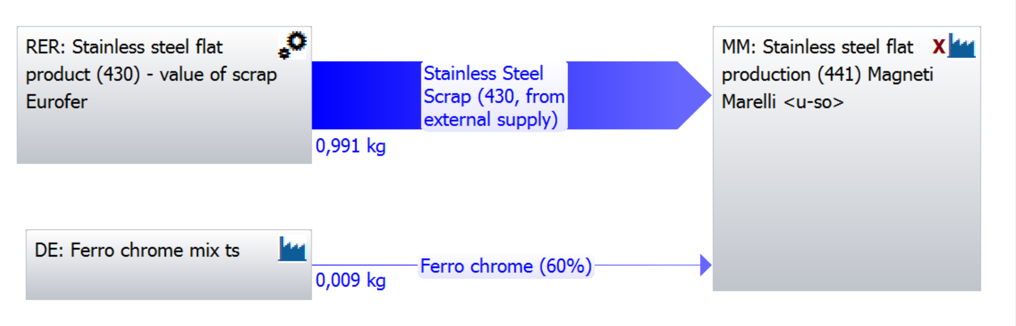
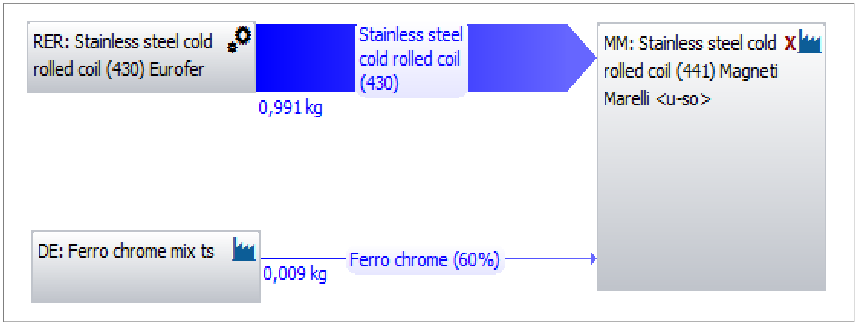


Figure B.3 - Stainless steel [AISI 430] flat product as modeled within Gabi software.



1. B.2 NON-METALS

Figure B.4 – Aluminium AlSi13Cu [EN AC-47000] including die-casting process as modeled within Gabi software.

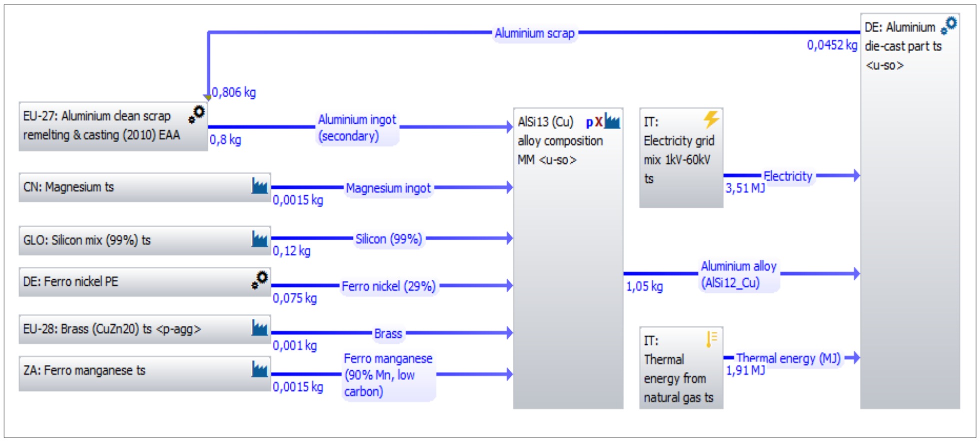
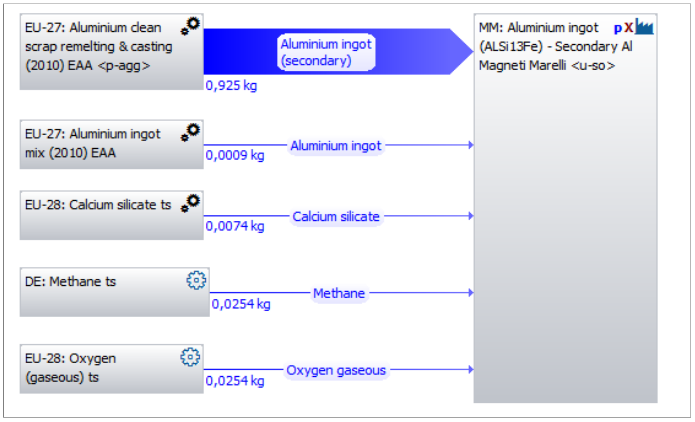


Figure B.5 - Aluminium AlSi13Fe [EN AC-47100] including ingot process as modeled within Gabi software.



B.3PLASTICS AND COMPOSITE

Figure B.6 – PPGF40 production process as modeled within Gabi software.

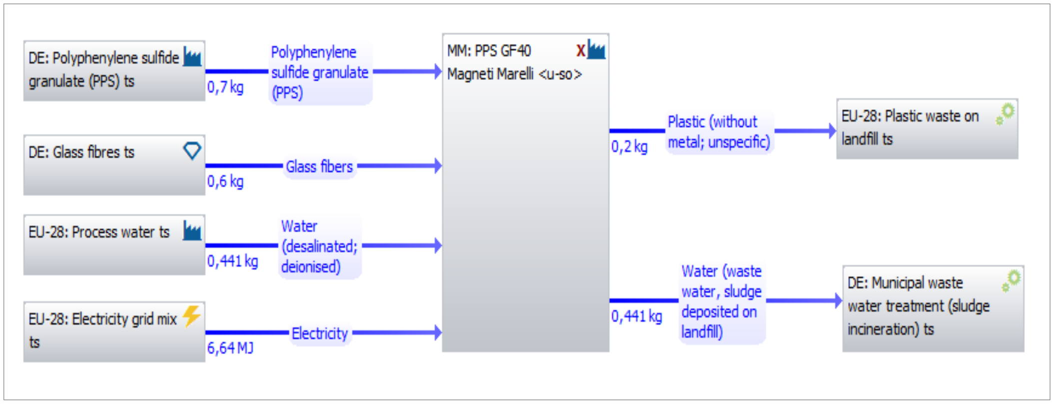


Figure B.7 – PA6-15CF-10GF production process as modeled within Gabi software.

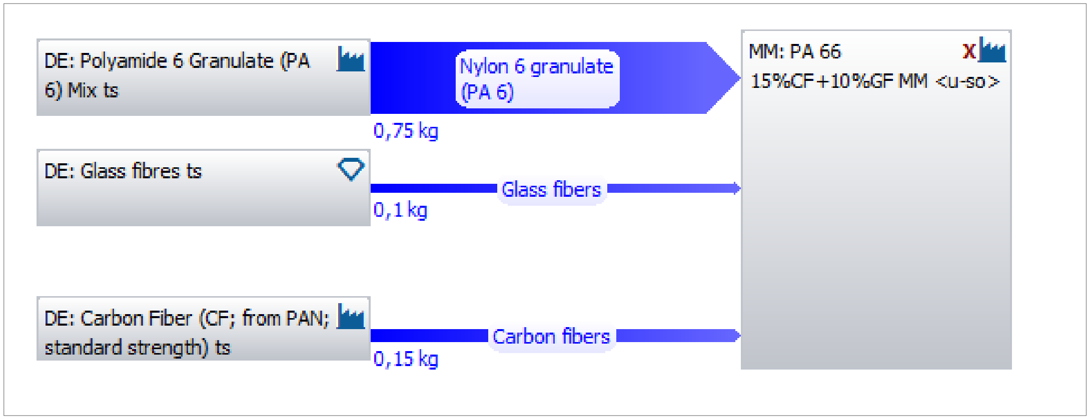


Figure B.8 – PA6GF60 production process as modeled within Gabi software.

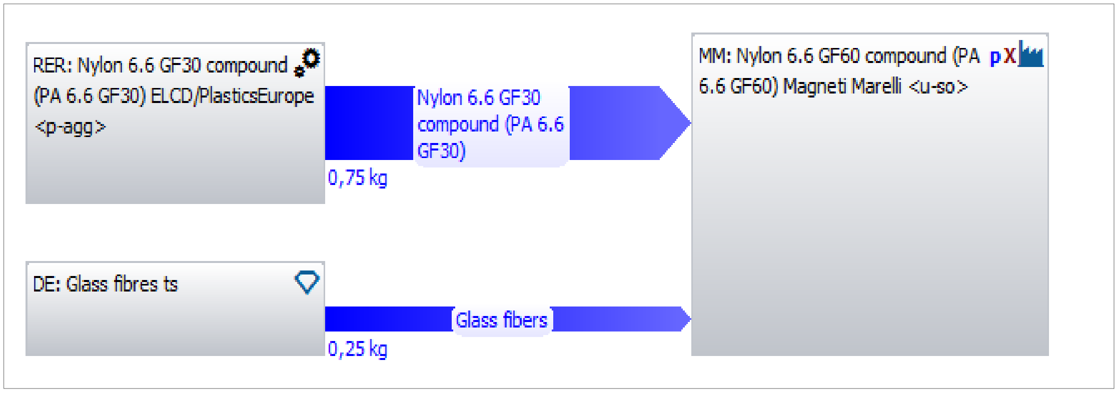


Figure B.9 - PBTGF30 production process as modeled within Gabi software.

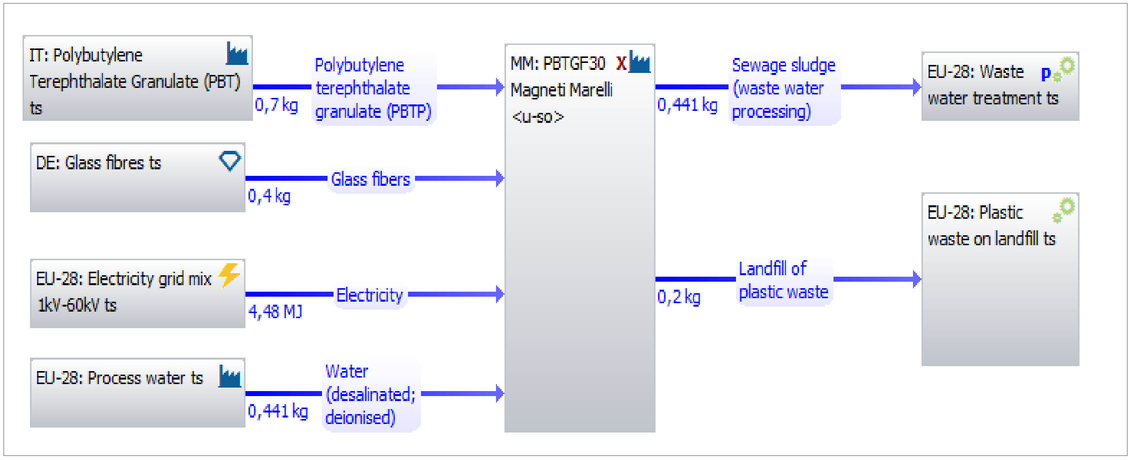


Figure B.10 - PBTGF50 production process as modeled within Gabi software.

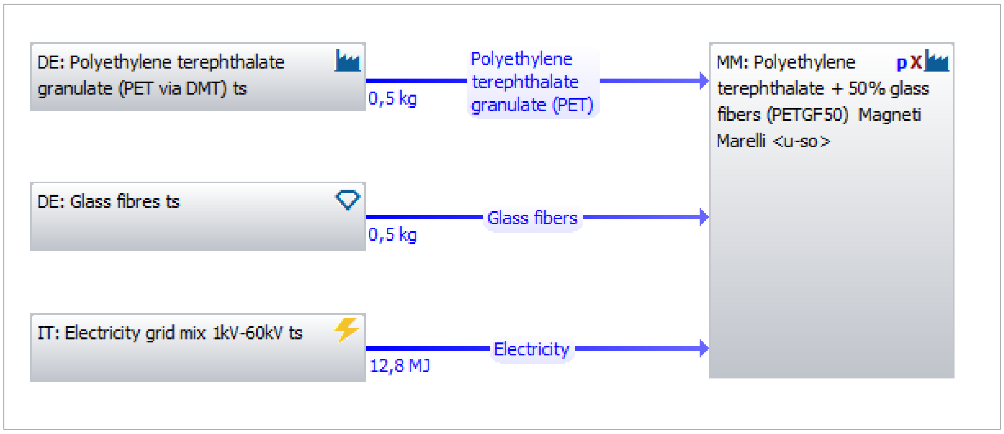
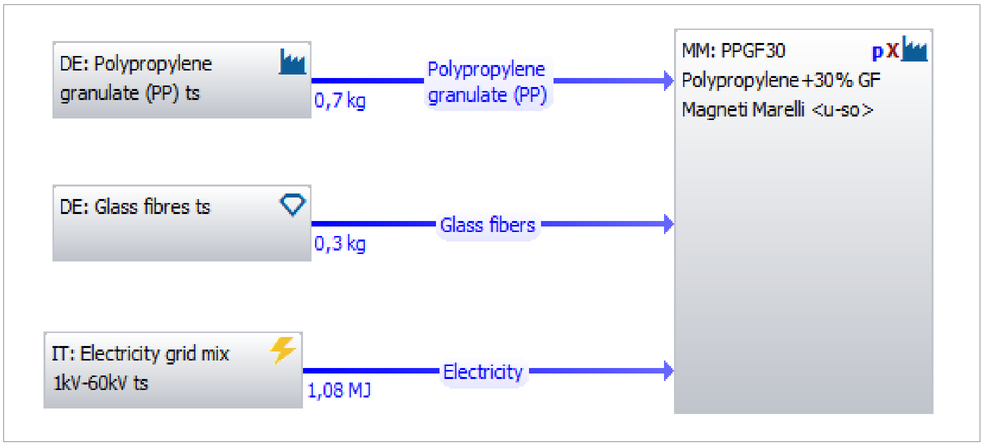


Figure B.11 – PPGF30 production process as modeled within Gabi software.



ANNEX C – LIFE CYCLE IMPACT ASSESSMENT (LCIA)

This section provides further information regarding LCA framework section of *Life Cycle Impact Assessment (LCIA),* which has been previously presented in CHAPTER 3. The impact assessment methods themselves are described in ISO 14042. In this standard a distinction is made between:

- ✓ Obligatory elements, such as Classification and Characterisation;
- ✓ Optional elements, such as Normalisation and Weighting.

C.1 CLASSIFICATION

The Inventory result of an LCA usually contains hundreds of different emissions and resource extraction parameters. The classification implies the assignment of specific environmental impacts to each component of the LCI. It is at this point that the decisions made during the definition phase of the scope and objective concerning the categories of environmental impact of interest come into play. The figure below illustrates a well-known set of classifications, called midpoint categories, and how it relates to the groups of damage they cause.These LCI results must be assigned to different impact categories. For instance, Table C.1 explains the classification approach, taking as example the attribution ofthe substances listed with the impact category selected. From Table C. could be seen that CO2 is responsible for Global warming potential impact, CFC affect global warming and ozone depletion. Therefor it is possible to assign emission to more than one impact category at the same time. What make different is the magnitude of the substances related to the specific impact. The incidence in this sense is defined in the CHARACTERIZATION C.2 step.

Table C.1 – Classification of Global Warming and Ozone Depletion attribution example.

	Impact category	
Life cycle inventory substances	Global warming	Ozone Depletion
Carbon dioxide (CO_2)	■	
Nitrogen dioxide (NO_2)	■	
Methane (CH_4)	■	
Chlorofluorocarbons (CFC)	■	■
Hydro chlorofluorocarbons (HCFC)	■	■
Methyl bromide (CH3Br)	■	■

C.2 CHARACTERISATION

Once the impact categories are defined and the LCI results are assigned to these impact categories, it is necessary to define characterisation factors. These factors should reflect the relative contribution of an LCI result to the impact category indicator result. For instance, on a time scale of 100 years the contribution of 1kg of CH_4 to Global Warming is 25 times as high as the emission of 1kg of CO_2. This means that if the characterisation factor of CO_2 is 1, the characterisation factor of CH_4 is 25. Thus, the impact category indicator result for Global Warming can be calculated by multiplying the LCI result with the characterisation factor.Once the impact categories have been defined, conversion factors (usually known as characterization or equivalence factors) use formulas to convert the LCI results into directly comparable impact indicators. In this way, different types of plastics and metals can be compared to their impact on global warming, for example. The Table C.2above provides some characterization factors commonly used for GWP impact category associated to the specific material (here are reported the first 16) ordered according to their scale. There are dozens of methods for categorization and characterization. Each of them links materials to impacts based on scientific research, and many materials have impacts in multiple categories. Typically, classification is supported by software that can calculate the impacts assigned based on real data or standard data tables.

Table C.2 - GHG characterization factor [Gabi software].

CML2001 – Apr. 13, Global Warming Potential (GWP 100 years)	1 [flow]= * kg CO_2-eq
1,1,1-Trichloroethane [Halogenated organic emissions to air]	1,46E+02
Carbon dioxide [Renewable resources]	1,00E+00
Carbon dioxide [Inorganic emissions to air]	1,00E+00
Carbon dioxide (biotic) [Inorganic emissions to air]	1,00E+00
Carbon dioxide (land use change) [Inorganic emissions to air]	1,00E+00
Carbon dioxide (peat oxidation) [Inorganic emissions to air]	1,00E+00
Carbon dioxide, land transformation [Inorganic emissions to air]	1,00E+00
Carbon tetrachloride [Halogenated organic emissions to air]	1,40E+03
Chloromethane (methyl chloride) [Halogenated organic emissions to air]	1,30E+01
Dichloromethane (methylene chloride) [Halogenated organic emissions to air]	8,70E+00
Halon (1211) [Halogenated organic emissions to air]	1,89E+03
Halon (1301) [Halogenated organic emissions to air]	7,14E+03
HBFC-2402 (Halon-2402) [Halogenated organic emissions to air]	1,64E+03
HBFC-2402 (Halon-2402) [Halogenated organic emissions to air]	1,64E+03
HFE 7100 [Halogenated organic emissions to air]	2,97E+02
Methane [Organic emissions to air (group VOC)]	2,50E+01

C.3 NORMALISATION

ISO 14042 defines normalisation as “calculation of the magnitude of indicator results relative to reference information”. The reference information may relate to a given community, person or other system, over a given period. Other reference information may also be adopted, of course, such as future target situation. The main aim of normalizing the (category) indicator results is to better understand the relative importance and magnitude of these results for each product system under study. Normalisation can also be used to check for inconsistencies, to provide and communicate information on the relative significance of the category indicator results and to prepare for additional procedures such as weighting or Interpretation (ISO 14042).

ISO 14042 states that in selecting the reference system due consideration should be given to the consistency of the spatial and temporal scales of the environmental mechanism and of the reference value. The reference value is the indicator result for a reference system. It is thus for a given impact category the sum of all the interventions associated with the reference system multiplied by the appropriate characterization factors:

- indicator $\text{result}_{cat,\ ref} = \sum_I m_{i,\ ref}$ x characterization $\text{factor}_{i,cat}$;
- normalized indicator result_{cat} = (indicator result_{cat} / indicator $\text{result}_{cat,\ ref}$).

Where:

- indicator $\text{result}_{cat,\ ref}$: indicator result for impact category *cat* and reference system *ref* (i.c. $kg*yr^{-1}$); the reciprocal of indicator $\text{result}_{cat,ref}$ is here referred to as the normalisation factor for impact category *cat* and reference system *ref*;
- $m_{i,\ ref}$:magnitude of intervention *i* (emission, resource extraction or land use) associated with the reference system *ref* (i.c. $kg*yr^{-1}$);
- characterization $\text{factor}_{i,cat}$: characterization factorfor intervention *i* and impact category *cat* (i.c. $kg*yr^{-1}$);
- normalized indicator result_{cat}: normalized indicator result for impact category *cat* (yr);
- indicator result_{cat}: indicator result for impact category *cat* (i.c. kg).

For the choice of reference system ISO provides several examples that can be used:

- ✓ The aggregate interventions for a given area in a reference year;
- ✓ The per capita interventions for a given area in a reference year;
- ✓ A baseline scenario, such as the calculated (category) indicator result for a given alternative product system;
- ✓ The aggregate interventions associated with the habits of consumption of a particular population in a reference year.

Among several normalization methods, one of the more used to represent European perspective is the EU25+3, considering 2009 as temporal horizon. The advantage of this method is that it is based on an absolute reference (impacts in Europe in 2009) and so it is possible to compare different case studies with one another.

C.4 WEIGHTING

Weighting is an optional step of impact assessment in which the (normalised) results for each impact category assessed are assigned numerical factors according to their relative importance, multiplied by these factors and possibly aggregated. Weighting is based on value-choices (e.g. expert panel). A convenient name for the result of the weighting step is “weighting result”, of which there is generally one for each alternative product system analysed. As a variation, thought, weighting may also yield several weighting results per product system, for instance for human health, ecosystem health and resources. ISO 14042 explicitly mentions the fact that weighting is based on value-choices and not on the natural sciences. Under the heading “weighting”, ISO again states that “the application and use of weighting methods shall be consistent with the goal and scope of the LCA study and shall be fully transparent”. As different individuals, organizations and societies may have different values, it is possible that different parties will arrive at different weighting results based on the same indicators results. ISO states that “all weighting methods and operations used shall be documented to provide transparency”. Inventory results and the (normalized) environmental profile arrived at prior to weighting are also to be made available, together with the weighting results. This ensures that:

- ✓ Trade off and other information remain available to decision-makers and to others;
- ✓ Users can appreciate the full extent and ramifications of the results.

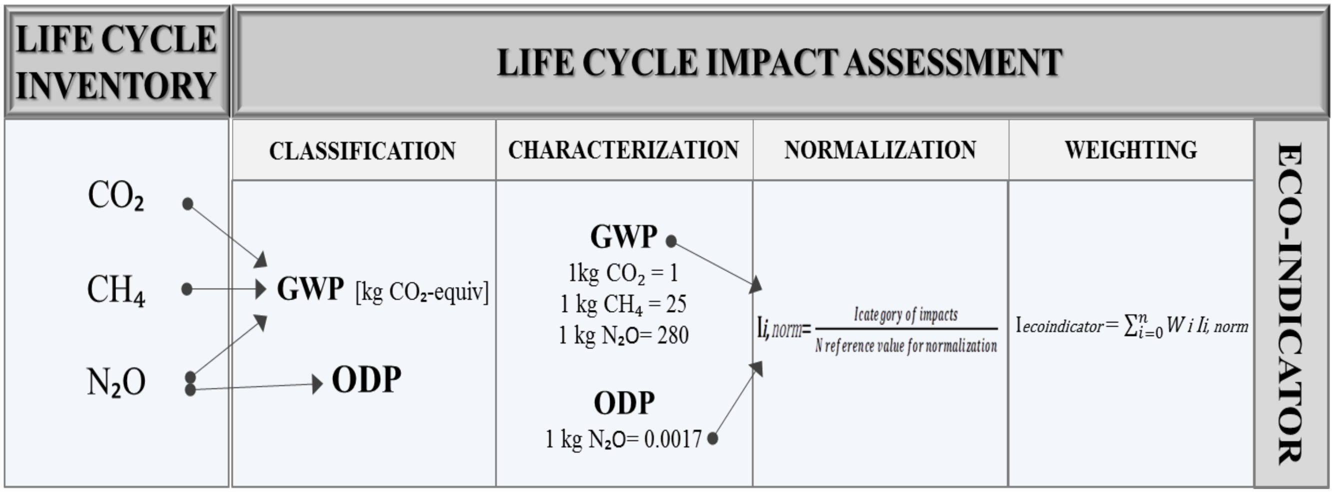
Finally ISO states that weighting shall not be used for comparative assertions disclosed to the public.

One of the main weighting methods is the “LCIA PE Survey 2012 (Europe)”. Such a method represents the subjective opinion of a number of LCA experts on the relevance of different impacts.

The weighting factors range of this method is based on a scale from 0 to 10, with 10 being the highest weighting factor and therefore having the highest relevance for the ecosystem under assessment. 0 thereby corresponds to an impact being not relevant at all.

A scheme of calculation methodology of LCIA is reported in Figure C.1.

Figure C.1 - Eco-indicator scheme of the calculation methodology.



ANNEX D - IMPACT CATEGORY INDICATORS

Following are described in deep each indicator selected in the impact assessment phase as well as the calculation method for their application.

D.1 CML 2001 IMPACT CATEGORY INDICATORS

The CML 2001 is an impact assessment method collection, which restricts quantitative modelling to relatively early stages in the cause-effect chain to limit uncertainties and group LCI results in so-called midpoint categories, according to themes. These themes are common mechanisms (e.g. climate change) or commonly accepted grouping (e.g. Ecotoxicity).

The data for the impact categories "CML 2001" are according to the information of the Institute of Environmental Sciences, Leiden University, and The Netherlands, published in a handbook and based on various different authors. The impact category indicators employed in the present study and considered by CML method 2001 updated in November 2009 are reported below:

✓	Abiotic Depletion Potential (ADP)	[kg Sb-Equiv.]
✓	Acidification Potential (AP)	[kg SO_2-Equiv.]
✓	Eutrophication Potential (EP)	[kg Phosphate-Equiv.]
✓	Fresh water aquatic Ecotoxicity Potential (FETP)	[kg DCB-Equiv.]
✓	Global Warming Potential (GWP 100 years)	[kg CO_2-Equiv.]
✓	Human Toxicity Potential (HTP)	[kg DCB-Equiv.]
✓	Marine aquaticEcotoxicity Potential (METP)	[kg DCB-Equiv.]
✓	Ozone layer Depletion Potential (ODP)	[kg R11-Equiv.]
✓	Photochemical Ozone Creation Potential (POCP)	[kg Ethene-Equiv.]
✓	Terrestric Ecotoxicity Potential (TETP)	[kg DCB-Equiv.]

Below a brief description of each of impact category above mentioned is reported.

D.1.1 ABIOTIC DEPLETION POTENTIAL (ADP$_{\mathbf{elements,\ fossil}}$)

The abiotic depletion potential (ADP) covers some selected natural resources as metal-containing ores, crude oil and mineral raw materials. Abiotic resources include raw materials from non-living resources that are non-renewable. This impact category describes the reduction of the global amount of non-renewable raw materials. Non-renewable means a period of at least 500 years. The abiotic depletion potential is split into two sub-categories, *elements* and *fossil*.Abiotic depletion potential (elements) covers an evaluation of the availability of natural elements like minerals and ores, including uranium ore. The reference substance for the characterisation factors is antimony. Two calculations of ADP (elements) from CML are integrated in GaBi6, one based on ultimate resources (i.e. the total mineral content in the earth crust) and one based on what is evaluated as being economically feasible to extract. The latter version is recommended by ILCD. The second sub-category is abiotic depletion potential (fossil), which includes the fossil energy carriers (crude oil, natural gas, coal resources). MJ is the respective unit.

D.1.2 ACIDIFICATION POTENTIAL (AP)

The acidification of soils and waters occurs predominantly through the transformation of air pollutants into acids. This leads to a decrease in the pH-value of rainwater and fog from 5.6 to 4 and below. Sulphur dioxide and nitrogen oxide and their respective acids (H_2SO_4 and HNO_3) produce relevant contributions. Ecosystems are damaged, so forest dieback is the most well-known impact. Acidification has direct and indirect damaging effects (such as nutrients being washed out of soils or an in-creased solubility of metals into soils). But even buildings and building materials can be damaged. Examples include metals and natural stones which are corroded or disintegrated at an increased rate. When analysing acidification, it should be considered that although it is a global problem, the regional effects of acidification can vary. Figure below displays the primary impact pathways of acidification.

The acidification potential is given in sulphur dioxide equivalents *(SO_2-eq.)*. The acidification potential is described as the ability of certain substances to build and release H^+ ions. Certain emissions can also have an acidification potential, if the given S-, N- and halogen atoms are set in proportion to the molecular mass of the emission. The reference substance is sulphur dioxide.

From an analytical point of view, AP value for each acid substance responsible for acidification is calculated as reported below:

$$AP_i = \frac{v_i / M_i}{v_{SO_2} / M_{SO_2}} \text{ [kg } SO_2\text{-Equiv.]}$$

Where:

v_i= Potential H^+ - equivalent, for mass unit, relative to substance *i*;

M_i = Molecular weight of substance *i*.

Finally total contribution to acidification is calculated by summation of all single contributions:

$$AP = \sum_i AP_i \cdot m_i \text{ [kg } SO_2\text{-Equiv.]}$$

D.1.3 EUTROPHICATION POTENTIAL (EP)

Eutrophication is the enrichment of nutrients in a certain place. Eutrophication can be aquatic or terrestrial. Air pollutants, wastewater and fertilisation in agriculture all contribute to eutrophication. The result in water is an accelerated algae growth, which in turn, prevents sunlight from reaching the lower depths. This leads to a decrease in photosynthesis and less oxygen production. Oxygen is also needed for the decomposition of dead algae. Both effects cause a decreased oxygen concentration in the water, which can eventually lead to fish dying and to anaerobic decomposition (decomposition without the presence of oxygen). Hydrogen sulphide and methane are produced. This can lead to the destruction of the eco-system, among other consequences. On eutrophicated soils an increased susceptibility of plants to diseases and pests is often observed, as is degradation of plant stability. If the nutrification level exceeds the amounts of nitrogen necessary for a maximum harvest, it can lead to an enrichment of nitrate. This can cause, by means of leaching, increased nitrate content in groundwater. Nitrate also ends up in drinking water. Nitrate at low levels is harmless from a toxic-logical point of view. Nitrite, however, is a reaction product of nitrate and toxic to humans. The causes of eutrophication are displayed in figure below. The eutrophication potential is calculated in phosphate equivalents *(PO_4-eq.)*. As with acidification potential, it is important to remember that the effects of eutrophication potential differ regionally.

All emissions of N and P to air, water and soil and of organic matter to water are aggregated into a single measure, as this allows both terrestrial and aquatic eutrophication to be assessed. The characterisation factors in PO_4-equivalents, NO_3-equivalents and O_2-equivalents are all interchangeable, and PO_4-equivalents are used.

From an analytical point of view, *“Eutrophication Potential”* is calculated by following expression:

$$EP_i = \frac{v_i \,/\, M_i}{v_{PO_4^{3-}} \,/\, M_{PO_4^{3-}}} \; [kg \;\; PO_4^{3-}\text{-}Equiv.]$$

Where:

v_i= Biomass growth potential expressed in kg di PO_4^{3-}-equivalent, for mass unit and relative to substance *i*;

M_i = molecular weight of substance *i*.

Finally total contribution is calculated by following expression:

$$EP_{tot.} = \sum_i EP_i \cdot Emission_i$$

D.1.4 ECOTOXICITY POTENTIAL

These three parameters relative to different aspects of toxicity are represented by the same unit of measure; it is the kg of *1,4 dichlorobenzene-equivalents*.

The “**Ecotoxicity potential”** of a certain substance can have effects towards aquatic ecosystems, soil and human health. It is important to distinguish the cases in which toxic substance is emitted in air, water or soil. So it is possible to distinguish between nine cases in the Ecotoxicity definition of a certain substance. They are described in the potential toxicity matrix:

$$pot.Toxicity_{subs\tan ce,compartment} = \begin{bmatrix} AETP_{subs,air} & AETP_{subs,water} & AETP_{subs,soil} \\ TETP_{subs,air} & TETP_{subs,water} & TETP_{subs,soil} \\ HTP_{subs,air} & HTP_{subs,water} & HTP_{subs,soil} \end{bmatrix}$$

Where:

AETP = Aquatic Ecotoxicity Potential;

TETP = Terrestrial Ecotoxicity Potential;

HTP = Human Toxicity Potential.

Relative subscripts indicate toxic substance and in what compartment it has been emitted.

“Human Toxicity Potential”, is calculated for each toxic substance by following expression:

$$HTP_{subs,comp} = \frac{MOS_{1,4-dichlorobenzene,air}}{MOS_{subs,comp}} \text{ [kg DCB-Equiv.]}$$

Where:

MOS = Margin of Safety.

Total HTP is obtained by following summation:

$$HTP_{tot} = \sum_{subs}\left(HTP_{subs,air} \cdot m_{subs,air}\right) + \sum_{subs}\left(HTP_{subs,water} \cdot m_{subs,water}\right) + \sum_{subs}\left(HTP_{subs,soil} \cdot m_{subs,soil}\right)$$

“Aquatic Ecotoxicity Potential” is obtained by following expression:

$$AETP_{subs,comp} = \frac{\left[\dfrac{PEC_{water,subs,comp}}{PNEC_{aquatic\_e\cos ystems,subs}}\right]}{\left[\dfrac{PEC_{water,1,4-dichlorobenzene,water}}{PNEC_{aquatic\_e\cos ystems,1,4-dichlorobenzene}}\right]} \text{ [kg DCB-Equiv.]}$$

Where:

PEC=Predicted Environmental Concentration;

PNEC=Predicted No Effect Concentration.

Total AETP is calculated by following expression:

$$AETP_{tot} = \sum_{subs}\left(AETP_{subs,air} \cdot m_{subs,air}\right) + \sum_{subs}\left(AETP_{subs,water} \cdot m_{subs,water}\right) + \sum_{subs}\left(AETP_{subs,soil} \cdot m_{subs,soil}\right)$$

Similarly **“Terrestrial Toxicity Potential”** is calculated:

$$TETP_{subs,comp} = \frac{\left[\dfrac{PEC_{agricultural-soil,subs,comp}}{PNEC_{aquatic\_ecosystems,subs}}\right]}{\left[\dfrac{PEC_{agricultural-soil,1,4-dichlorobenzene,industrial-soil}}{PNEC_{terrestrial\_ecosystems,1,4-dichlorobenzene}}\right]} \text{ [kg DCB-Equiv.]}$$

Where:
PEC=Predicted Environmental Concentration;
PNEC=Predicted No Effect Concentration.
Single contributions are then aggregated:

$$TETP_{tot} = \sum_{subs}\left(TETP_{subs,air} \cdot m_{subs,air}\right) + \sum_{subs}\left(TETP_{subs,water} \cdot m_{subs,water}\right) + \sum_{subs}\left(TETP_{subs,soil} \cdot m_{subs,soil}\right)$$

D.1.5 GLOBAL WARMING POTENTIAL (GWP)

The mechanism of the greenhouse effect can be observed on a small scale, as the name suggests, in a greenhouse. These effects also occur on a global scale. The occurring short-wave radiation from the sun comes into contact with the earth’s surface and is partially absorbed (leading to direct warming) and partially reflected as infrared radiation. The reflected part is absorbed by greenhouse gases in the troposphere and is re-radiated in all directions, including back to earth. This results in a warming effect at the earth’s surface. In addition to the natural mechanism, the greenhouse effect is enhanced by human activities. Greenhouse gases, believed to be anthropogenically caused or increased, include carbon dioxide, methane and CFCs. Figure below shows the main processes of the anthropogenic greenhouse effect. An analysis of the greenhouse effect should consider the possible long-term global effects. The Global Warming Potential is calculated in carbon dioxide equivalents *(CO_2 -eq.)*, meaning that the greenhouse potential of an emission is given in relation to CO_2. Since the residence time of gases in the atmosphere is incorporated into the calculation, a time range for the assessment must also be specified. A usual period is 100 years.

From an analytical point of view, *"Global Warming Potential"* is calculated for each substance emitted in atmosphere recognized as responsible of greenhouse effect, taking into account its relative permanence time as long as it can be considered degraded.

The analytical expression is the following:

$$GWP_{i,T} = \frac{\int_0^T a_i \cdot c_i(t)dt}{\int_0^T a_{CO_2} \cdot c_{CO_2}(t)dt} \text{ [kg CO2-Equiv.]}$$

Where:

a_i= Heat absorption coefficient of gas i; $c_i(t)$ = Gas i concentration at time t; T = Integration time (100, 200 or 500 years).

Finally total contribution is calculated: $GWP_{tot.} = \sum_i GWP_i \cdot amount\_emission_i$

Where: $amount\_emission_i$ = amount of gas *i emission*, in kg.

D.1.6 OZONE LAYER DEPLETION POTENTIAL (ODP)

Ozone is created in the stratosphere by the disassociation of oxygen atoms that are exposed to short-wave UV-light. This leads to the formation of the so-called ozone layer in the stratosphere (15-50 km high). About 10% of this ozone reaches the troposphere through mixing processes. In spite of its minimal concentration, the ozone layer is essential for life on earth. Ozone absorbs the short-wave UV-radiation and releases it in longer wavelengths. As a result, only a small part of the UV-radiation reaches the earth. Anthropogenic emissions deplete ozone. This is well-known from reports on the hole in the ozone layer. The hole is currently confined to the region above Antarctica; however further ozone depletion can be identified, albeit not to the same extent, over the mid-latitudes (e.g. Europe). The substances which have a depleting effect on the ozone can essentially be divided into two groups; the chlorofluorocarbons (CFCs) and the nitro-gen oxides (NO_X). Figure below depicts the procedure of ozone depletion. One effect of ozone depletion is the warming of the earth's surface. The sensitivity of humans, animals and plants to UV-B and UV-A radiation is of particular importance. Possible effects are changes in growth or a decrease in harvest crops (disruption of photosynthesis), indications of tumours (skin cancer and eye diseases) and a decrease of sea plankton, which would strongly affect the food chain. In calculating the ozone depletion potential, the anthropogenically-released halogenated hydrocarbons, which can destroy many ozone molecules, are recorded first. The Ozone Depletion Potential (ODP) results from the calculation of the potential of different ozone relevant substances.

A scenario for a fixed quantity of emissions of a CFC reference *(CFC $_{11}$)* is calculated, resulting in an equilibrium state of total ozone reduction. The same scenario is considered for each substance under study where CFC_{11} is replaced by the quantity of the substance. This leads to the ozone depletion potential for each respective substance, which is given in CFC_{11}-equivalents. An evaluation of the ozone depletion potential should take into consideration the long term, global and partly irreversible effects.

From an analytical point of view, *"Ozone Depletion Potential"*, expressed in kg of CFC-$_{11}$, is therefore calculated for each gas emitted in atmosphere, recognized as potentially responsible for ozone layer damage:

$$ODP_i = \frac{\delta[O_3]_i}{\delta[O_3]_{R11}}$$

Where:

$\delta[O_3]_i$ = Ozone degradation model, caused by substance *i*;

$\delta[O_3]_{R11}$ = Ozone degradation model, caused by CFC-11.

Similarly total contribution is calculated:

$$ODP_i = \sum_i ODP_i \cdot Emission_i[kg].$$

D.1.7 PHOTOCHEMICAL OZONE CREATION POTENTIAL(POCP)

Despite playing a protective role in the stratosphere, ozone at ground level is classified as a damaging trace gas. Photochemical ozone production in the troposphere, also known as summer smog, is suspected to dam-age vegetation and material. High concentrations of ozone are toxic to humans.

Radiation from the sun and the presence of nitrogen oxides and hydrocarbons incur complex chemical reactions, producing aggressive reaction products, one of which is ozone. Nitrogen oxides alone do not cause high ozone concentration levels. Hydrocarbon emissions occur from incomplete combustion, in conjunction with petrol (storage, turnover, refuelling) or from solvents. High concentrations of ozone arise when temperature is high, humidity is low, air is relatively static and there are high concentrations of hydrocarbons. Today it is assumed that the existence of NO and CO reduces the accumulated ozone to NO_2, CO_2 and O_2. This means that high concentrations of ozone do not often occur near hydrocarbon emission sources. Higher ozone concentrations more commonly arise in areas of clean air, such as forests, where there is less NO and CO. In Life Cycle Assessments photochemical ozone creation potential (POCP) is referred to in ethylene-equivalents *(C_2H_4-eq.)*. During analysis it is important to note that the actual ozone concentration is strongly influenced by the weather and by the characteristics of local conditions. From an analytical point of view, POCP is calculated by following expression:

$$POCP_i = \frac{a_i / b_i}{a_{c_2H_4} / b_{C_2H_4}} \text{ [kg } C_2H_4\text{-Equiv.]}$$

Where:

$POCP_i$ = "Photochemical Oxidant Potential" relative to substance *i*;

a_i= Variation in active oxygen concentration due to volatile organic substance i emission;

b_i = Integration on time of volatile organic substance i emission;

$a_{C_2H_4}$ = Variation in active oxygen concentration due to C_2H_4 emission;

$b_{C_2H_4}$ = Integration on time of C_2H_4 emission;

Similarly total contribution is calculated:

$$POCP_{tot.} = \sum_i POCP_i \cdot Emission_i [kg].$$

D.2 PRIMARY ENERGY DEMAND FROM RENEWABLE AND NON-RENEWABLE RESOURCES (PED$_{\text{gross calorific value}}$)

Primary energy demand (PED) is often difficult to determine due to the various types of energy sources. Primary energy demand is the quantity of energy directly withdrawn from the hydrosphere, atmosphere or geosphere or energy source without any anthropogenic changes. For fossil fuels and uranium, PED would be the amount of resources withdrawn expressed in their energy equivalents (i.e. the energy content of the raw material). For renewable resources, the energy characterised by the amount of biomass consumed would be described. PED for hydropower would be based on the amount of energy that is gained from the change in the potential energy of the water (i.e. from the height difference). The following primary energies are designated as aggregated values:

- The total "Primary energy consumption non-renewable," given in MJ, essentially characterises the gain from the energy sources: natural gas, crude oil, lignite, coal and uranium. Natural gas and crude oil will be used both for energy production and as material constituents, such as in plastics. Coal will primarily be used for energy production. Uranium will only be used for electricity production in nuclear power stations.

- The total “Primary energy consumption renewable,” given in MJ, is generally accounted for separately and comprises hydropower, wind power, solar energy and biomass.

It is important that end use energy (e.g. 1 kWh of electricity) and primary energy are not confused with each other; otherwise, the efficiency loss in production and supply of the end energy will not be accounted for. The energy content of the manufactured products will be considered to be feedstock energy content. It will be characterised by the net calorific value of the product. It represents the still-usable energy content that results, such as incineration with energy recovery.

D.3 TOTAL FRESHWATER CONSUMPTION [KG]

The Total freshwater consumption is calculated according to this formula:

Total freshwater consumption = total freshwater use (water input) – total freshwater release from techno sphere (water outputs)

= water vapour (including water evaporated from input products and including evapotranspiration of rain water from plants)

+ water incorporated in product outputs + water (freshwater, incl. rainwater released to sea).

In the respective GaBi quantity, this calculation approach is implemented by summing up all inputs (characterization factor 1) and then subtracting all degradative output flows (characterization factor -1).

Please note that in general, only blue water (surface and ground water) is considered. Therefore, rain water is typically excluded from freshwater consumption and the focus is only on blue water consumption.

In detail, the flow based calculation is:

Blue water consumption = Fresh water + Ground water + Lake water (incl. turbined) + River water (incl. turbined) + water (fossil groundwater) - Cooling water to lake - Cooling water to river - Processed water to groundwater - Processed water to lake - Processed water to river - Turbined water to lake - Turbined water to river

ANNEX E – SOCIAL LIFE CYCLE ASSESSMENT (SLCA)

In this section is reported the method used for the calculation of the allocation factor and a full description of all the dimension and impact to assess.

E.1 ALLOCATION METHOD

E. 1 – S-LCA allocation method.

Indicator	Unit	Formula
a) Number of employees at the site	Employees at site	
b) Number of employees working at the specific production line	Employees at LCS	
c) Total production at site level	ton	
d) Total production of the product assessed	ton	
e) Average number of working hours per employee per week at the site	hours	
f) Average number of working hours per employee per week at the production line	hours	
g) Hours worked to produce 1 unit of any product at the site	hours per site	$\frac{a*e*52}{c}$
h) Hours worked to produce 1 unit of the product assessed	hours per LCS	$\frac{b*e*52}{d}$
i) Allocation factor		$\frac{g}{h}$

E.2 PERFORMANCE INDICATOR

E.2.1 WORKERS

Table E.2 - SLCA performance indicator data collection workers category.

Social topics	Performance Indicators	Unit
Health and safety	Number of hours of health & safety training given during the reporting period	hours
	Average number of incidents during the reporting period	number
Wages	Percentage of workers whose wages meet at least the legal or industry minimum wage and their provision fully complies with all applicable laws	%
	Percentage of workers who are paid a living wage	%
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	%
Working hours	Percentage of workers who exceeded 48 hours of work per week regularly during the reporting period	%

Child labour	Number of hours of child labour identified during the reporting period.	hours
	Number of actions during the reporting period targeting business partners to raise awareness of the issue of child labour	actions
Forced labour	Number of hours of forced labour identified during the reporting period.	hours
	Number of actions during the reporting period targeting business partners to raise awareness of the issue of forced labour	actions
Discrimination	Number of complaints identified during the reporting period related with discrimination	complaints
	Number of actions taken during the reporting period to increase staff diversity and/or promote equal opportunities	actions
Freedom of association and collective bargaining	Percentage of workers identified during the reporting period who are members of associations able to organize themselves and/or bargain collectively	%
Employment relationship	Percentage of workers who have documented employment conditions	%
Training and education	Number of hours of training per employee during the reporting period.	hours
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	%
Job satisfaction and engagement	Percentage of workers who participated in a job satisfaction and engagement survey during the reporting period	%
	Worker turnover rate during the reporting period	%

E.2.2 CONSUMERS

Table E.3 - SLCA performance indicator data collection consumer's category.

Social topics	Performance Indicators	Unit
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
	Number of complaints identified during the reporting period related to consumer health and safety.	complaints
Experienced well-being	Composite measure of experienced well-being (1 to 10)	absolute metric

E.2.3 LOCAL COMMUNITIES

Table E.4 - SLCA performance indicator data collection local community's category.

Social topics	Performance Indicators	Unit
Health and safety	Number of programmes during the reporting period to enhance community health and safety.	programmes
	Number of adverse impacts on community health or safety identified during the reporting period.	adverse impacts
Access to tangible resources	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
Local capacity building	Number of programs 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
Community engagement	Number of programmes or events targeting community engagement during the reporting period.	programmes
Employment	Number of new jobs created during the reporting period.	new jobs
	Number of jobs lost during the reporting period.	jobs lost

E.3 STAKEHOLDER GROUP

E.3.1 WORKERS

All workers and employers have the right to establish and to join organizations of their choice, without prior authorization, to promote and defend their respective interests, and to negotiate collectively with other parties. They should be able to do this freely, without interference by other parties or the state, and should not be discriminated as a result of union membership. The right to organize includes the right of workers to strike, the rights of organizations to draw up their constitutions and rules, to elect their representatives in full freedom, to organize their activity freely and to formulate their programmes. Freedom of association, the Right to Organize and Collective Bargaining are assessed and monitored via this subcategory.

The assessment aims to verify the compliance of the organization with freedom of association and collective bargaining standards. In particular: whether the workers are free to form and join association (s) of their choosing even when it could damage the economic interest of the organization, or whether the workers have the right to organize unions, to engage in collective bargaining and to strike.

The right to freedom of association is referenced in several human rights instruments such as the Universal Declaration of Human Rights. According to the ILO Decent Work Agenda, it consists of four strategic objectives that should be achieved to foster a sustainable society: the protection of standards and fundamental principles and rights at work, employment promotion, social protection and social dialogue. The protection of fundamental principles and rights at work is strictly associated with the promotion of compliance with ‘core labour standards’ identified in the ILO 1998 Declaration on Fundamental Principles and Rights at Work, including freedom of association and the effective recognition of the right to collective bargaining. The ILO´s approach aims to develop and to insure decent working conditions: all men and women must have the ability to obtain decent and productive work in conditions of freedom, equity, security and human dignity. These are meaningful conditions to reach sustainable economy and society, and consequently to reach sustainable development.

E.3.1.1 HEALTH AND SAFETY

The purpose of occupational health is the promotion and maintenance of the highest degree of physical, mental and social well-being of workers in all occupations; the prevention of workers leaving their jobs on the grounds of ill health caused by their working conditions; the protection of workers against risks incurred at work as a result of factors detrimental to health; the placing and maintenance of workers in an occupational environment adapted to their physiological and psychological capabilities; taking gender differences into account and, to summarise, the adaptation of work to each person and of each person to his/her job.

E.3.1.2 WAGES

Wages paid for a normal working week should meet at least the minimum wage, established either by law, collective bargaining agreement or an industry standard. Living wage means that wages received by a worker for a standard working week in a particular place should be sufficient to provide a decent standard of living for the worker and his or her family.

E.3.1.3SOCIAL BENEFITS

In addition to wages, the provision of social benefits should comply fully with all applicable laws. Five basic categories of social security benefits are often included and are paid based upon recorded workers' earnings: retirement, disability, dependents, survivor benefit and, in the case of termination of employment, severance pay.

E.3.1.4 WORKING HOURS

The number of working hours is defined by applicable laws and industry standards on working hours and public holidays. The normal working week, excluding overtime, should not exceed limits laid down by law or 48 hours for hourly workers. Workers should be provided with at least one day oı following every six consecutive days of working. Overtime work is voluntary, compensated at a premium rate in accordance with either the law or applicable collective agreement, does not exceed 12 hours per week, and is not demanded on a regular basis. (1-48 hours for 6 working days per week).

E.3.1.5 CHILD LABOUR

Child labour is work that deprives children of their childhood, their potential and their dignity, and is harmful to physical and mental development. In its most extreme forms, child labour involves children being enslaved, separated from their families, exposed to serious hazards and illnesses and/or left to fend for themselves on the streets of large cities.

E.3.1.6 FORCED LABOUR

Forced labour is all work or service which is exacted from any person under the threat of any penalty and for which the person has not offered him/her voluntarily. Forced labour includes practices such as the use of compulsory prison labour by private business entities, debt bondage, indentured servitude and human tracking. Workers should be free to leave the workplace and manage their own time while not on duty, without interference or intimidation from management or security guards. If workers choose to leave their jobs, they should be free to do so, provided they have fulfilled their agreed obligations under a recognised employment contract.

E.3.1.7 DISCRIMINATION

Discrimination refers to any distinction, exclusion or preference that has the effect of nullifying or impairing equality of opportunity or treatment. In order to prevent discrimination, a company should not engage in or support discrimination in hiring, remuneration, access to training, promotion, termination, or retirement which is based on race, national or social origin, caste, birth, religion, disability, gender, sexual orientation, family responsibilities, marital status, union membership, political opinions, state of health (including HIV/AIDS status), age, or any other circumstance that could give rise to discrimination.

E.3.1.8 FREEDOM OF ASSOCIATION AND COLLECTIVE BARGAINING

Workers should have the right to establish and to join organizations of their choice, without prior authorization, to promote and defend their respective interests, and to negotiate collectively with other parties. They should be able to do this freely, without interference by other parties or the state, and should not be discriminated against as a result of union membership. The right to organize includes the right of workers to strike, the rights of organizations to draw up their constitutions and rules, to freely elect their representatives, to organize their activities without restriction and to formulate their programmes.

E.3.1.9 EMPLOYMENT RELATIONSHIP

Work should be performed based on a recognised employment relationship established through national law and practice. Obligations to workers under labour or social security laws and regulations based on a normal employment relationship should not be circumvented by the use of labour-only contracting, subcontracting, and home-working arrangements, contracting of self-employed workers, trainee and apprenticeship schemes, or the excessive use of fixed-term contracts of employment. All parties should be aware of their rights and responsibilities, and should have access to an effective grievance mechanism.

E.3.1.10 TRAINING AND EDUCATION

Training and education refers to workplace policy and initiatives to expand workers' capabilities and skills, thus increasing their capacity and employability. Capacity development is important as it contributes to the growth of human capital within the organization.

E.3.1.11 WORK-LIFE BALANCE

Work-life balance concerns workers having choices over when, where and how they work. The balance between the commitments of work and those of private life is central to workers' well-being. Work-life balance is achieved when the worker's right to a fulfilled life at and outside work is accepted and respected, for the benefit of both the worker and the employer.

E.3.1.12 JOB SATISFACTION AND ENGAGEMENT

Job satisfaction is the extent to which workers are satisfied with their job, their employer; intend to stay and to be loyal to their employers. Many factors influence the job satisfaction levels of the workers of an organization, for example, work content, responsibilities and career opportunities.

E.3.2 CONSUMERS

Consumer health and safety refers to the consumers' rights to be protected against products and services that may be hazardous to health or life (ISO 26000, 2008). Customers (end users) expect products and services to perform their intended functions satisfactorily and not pose a risk to their health and safety.

E.3.2.1 HEALTH AND SAFETY

Products are expected to perform their intended functions satisfactorily and not pose a risk to consumers' health and safety. This social topic addresses both risks and the positive impacts that products may have on the health and safety of the end-users of products.

E.3.2.2 EXPERIENCED WELL-BEING

Experienced well-being is the self-evaluation of positive and negative feelings or emotional states, with reference to a particular experience. This social topic measures the well-being the consumer experiences associated with the use of a product.

E.3.3 LOCAL COMMUNITIES

Economic development sometimes leads to the large-scale migration of individuals seeking employment. Involuntary resettlement may occur if organizations directly or indirectly dispossess individuals or groups of individuals of their land or resources. In the case of migrant workers entering a community, the organization should consider how well workers will integrate with more permanent residents. Organizations should provide opportunities for communication and education between migrant workers and permanent residents to minimize risks, such as violence and prostitution. If operations require human relocation, organizations should engage in due diligence and procedural safeguards. These safeguards include comprehensive impact assessments, prior consultation and notification, provision of legal remedies, fair and just compensation and adequate relocation (see UN Global Compact, Access to Adequate Housing). Resettlement is considered involuntary when groups are not offered the right to refuse acquisition that leads to displacement. Involuntary resettlement may occur even when the dispossessed do not have legal claim to the land or resources. The assessment aims to assess whether organizations contribute to delocalization, migration or "involuntary resettlement" within communities and whether populations are treated adequately.As organizations enter emerging markets there is potential for delocalization and migration to occur. Involuntary resettlement can lead to long-term social and economic hardships for affected populations. Organizations should be aware of these effects and understand that states may place economic development goals above the human rights of certain populations. Organizations should engage with at risk populations and respond to their concerns.With regard to the migration of labor, while the migration of relatively skilled workers can encourage economic development in host countries, home countries experience a loss of human capital. At the same time, remittances to family members in home countries play an important role in theeconomicdevelopment of less developed countries. In addition, migrant workers may return home with new skills that contribute to economic development in their home country.

E.3.3.1 HEALTH AND SAFETY

The extent to which the company or facility works to prevent and mitigate adverse impacts, or enhance positive impacts on the health and safety of the local community, with particular attention to vulnerable groups such as indigenous peoples and women.

E.3.3.2 ACCESS TO MATERIAL RESOURCES

The extent to which the company or facility works to prevent and mitigate adverse impacts on, or to restore and improve community access to, tangible resources and infrastructure. It also includes respect for indigenous peoples' and women's land rights and tangible forms of cultural heritage.

E.3.3.3 LOCAL CAPACITY BUILDING

The extent to which the company or facility works to contribute to the long-term development of local communities by enhancing and unlocking their human potential through improved access to knowledge, information, technology and skills.

E.3.3.4 COMMUNITY ENGAGEMENT

The extent to which the company or facility engages with community stakeholders through ongoing open dialogue and responds to their concerns and inquiries fairly and promptly, in order to continuously foster greater trust and the relationship with the local community. Particular attention needs to be paid to engaging representatives of vulnerable groups such as indigenous peoples and women.

E.3.3.5 LOCAL EMPLOYMENT

The extent to which, the company or facility creates new jobs. Employment improves the economic livelihood of the workforce and their families. Employment also creates ripple effects of sustainable development across the community.

ANNEX F – LCIA RESULTS

F.1 STRATEGY 1

F.1.1 AIR INTAKE MANIFOLD

Table F.1 - LCIA Results for air intake manifold project [standard design].

	AIR INTAKE MANIFOLD					
	Standard design *[PAGF30]*					
Impact categories	Materials	Logistic	Manufacturing	Use	EoL (W)	EoL (B)
Abiotic Depletion (ADP elements) [kg Sb eq.]	1,89E-04	8,29E-09	1,49E-07	6,36E-07	2,96E-08	5,79E-07
Abiotic Depletion (ADP fossil) [MJ]	1,85E+02	3,08E+00	1,43E+01	1,31E+02	1,98E+00	1,92E+00
Acidification Potential (AP) [kg SO2 eq.]	4,97E-02	1,08E-03	2,67E-03	7,10E-03	3,86E-04	1,12E-03
Eutrophication Potential (EP) [kg Phosphate eq.]	1,02E-02	2,51E-04	1,79E-04	1,26E-03	3,68E-04	9,36E-05
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	3,02E-02	5,24E-04	1,57E-03	4,96E-02	6,23E-04	3,34E-04
Global Warming Potential (GWP 100 years) [kg CO2 eq.]	1,45E+01	2,22E-01	9,95E-01	8,52E+00	1,41E-01	4,73E+00
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	3,14E-01	5,98E-03	3,41E-02	2,92E-01	4,60E-03	8,02E-02
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	4,27E+02	1,65E+00	5,44E+01	1,36E+02	1,39E+01	1,13E+01
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	3,75E-10	3,89E-12	3,88E-10	3,63E-13	5,69E-13	6,21E-13
Photochemical. Ozone Creation Potential (POCP) [kg Ethene eq.]	6,86E-03	-3,94E-04	2,10E-04	1,06E-03	4,32E-05	5,16E-05
Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	1,49E-02	1,64E-03	2,80E-03	4,05E-03	2,60E-03	6,82E-04
Primary energy demand [MJ]	2,03E+02	3,43E+00	1,87E+01	1,48E+02	2,46E+00	2,88E+00

Table F.2 - LCIA Results for air intake manifold project [innovative design].

	AIR INTAKE MANIFOLD					
	Innovative design *[PPGF35]*					
Impact categories	Materials	Logistic	Manufacturing	Use	EoL (W)	EOL (B)
Abiotic Depletion (ADP elements) [kg Sb eq.]	9,99E-05	7,14E-09	1,12E-07	5,28E-07	2,54E-08	4,97E-07
Abiotic Depletion (ADP fossil) [MJ]	9,61E+01	2,65E+00	1,07E+01	1,09E+02	1,70E+00	1,64E+00
Acidification Potential (AP) [kg SO2 eq.]	1,66E-02	9,28E-04	2,00E-03	5,90E-03	3,31E-04	9,60E-04
Eutrophication Potential (EP) [kg Phosphate eq.]	1,95E-03	2,16E-04	1,34E-04	1,05E-03	3,16E-04	8,03E-05
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	3,03E-03	4,51E-04	1,19E-03	4,12E-02	5,34E-04	2,86E-04
Global Warming Potential (GWP 100 years) [kg CO2 eq.]	4,28E+00	1,92E-01	7,45E-01	7,07E+00	1,21E-01	4,06E+00
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	7,12E-02	5,15E-03	2,55E-02	2,42E-01	3,94E-03	6,88E-02
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	1,61E+02	1,42E+00	4,07E+01	1,13E+02	1,19E+01	9,72E+00
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	3,65E-10	3,35E-12	2,91E-10	3,01E-13	4,88E-13	5,32E-13
Photochemical. Ozone Creation Potential (POCP) [kg Ethene eq.]	4,12E-03	-3,39E-04	1,57E-04	8,78E-04	3,70E-05	4,42E-05
Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	6,27E-03	1,41E-03	2,10E-03	3,37E-03	2,23E-03	5,85E-04
Primary energy demand [MJ]	1,06E+02	2,95E+00	1,40E+01	1,23E+02	2,11E+00	2,47E+00

F.1.2 PEDALBOX SUPPORT

Table F.3 - LCIA Results for pedal box support project [standard design].

	PEDALBOX SUPPORT					
	Standard design *[PPGF30]*					
Impact categories	Materials	Logistic	Manufacturing	Use	EoL (W)	EoL (B)
Abiotic Depletion (ADP elements) [kg Sb eq.]	4,94E-03	4,38E-08	4,21E-09	4,64E-07	2,49E-08	-4,23E-07
Abiotic Depletion (ADP fossil) [MJ]	4,16E+01	1,04E+00	8,72E-01	9,89E+01	1,11E+00	-7,86E+00
Acidification Potential (AP) [kg SO2 eq.]	6,08E-03	1,65E-04	1,57E-04	5,74E-03	2,10E-04	2,02E-04
Eutrophication Potential (EP) [kg Phosphate eq.]	1,31E-03	1,68E-05	3,64E-05	9,17E-04	1,75E-04	2,83E-04
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	1,82E-01	1,30E-04	3,71E-04	3,72E-02	3,10E-04	-9,28E-04
Global Warming Potential (GWP 100 years) [kg CO2 eq.]	1,84E+00	8,28E-02	6,33E-02	5,91E+00	8,07E-02	7,33E-01
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	2,50E+00	2,89E-03	1,55E-03	2,01E-01	2,67E-03	-2,02E-02
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	4,18E+02	4,94E+00	8,17E-01	1,03E+02	7,49E+00	-5,09E+01
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	5,15E-08	1,54E-11	2,91E-13	4,45E-12	8,11E-13	-2,60E-11
Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	5,60E-04	1,44E-05	-4,43E-05	8,00E-04	2,25E-05	-8,25E-06
Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	1,11E-02	3,67E-05	1,43E-04	2,96E-03	1,21E-03	-7,54E-05
Primary energy demand [MJ]	5,62E+01	1,88E+00	9,88E-01	1,12E+02	1,52E+00	-1,65E+01
Total water consumption [kg]	3,07E-01	2,70E-03	6,78E-05	1,74E-02	1,43E-03	-2,20E-02

Table F.4 - LCIA Results for pedal box support project [innovative design].

	PEDALBOX SUPPORT					
	Innovative design *[PPNF45]*					
Impact categories	Materials	Logistic	Manufacturing	Use	EoL (W)	EOL (B)
Abiotic Depletion (ADP elements) [kg Sb eq.]	2,12E-03	3,73E-08	7,95E-09	4,33E-07	2,39E-08	-1,46E-07
Abiotic Depletion (ADP fossil) [MJ]	3,16E+01	8,91E-01	1,64E+00	9,25E+01	1,05E+00	-5,00E+00
Acidification Potential (AP) [kg SO2 eq.]	4,09E-03	1,41E-04	2,89E-04	5,36E-03	1,98E-04	-1,87E-03
Eutrophication Potential (EP) [kg Phosphate eq.]	8,02E-04	1,43E-05	6,69E-05	8,57E-04	1,63E-04	-4,46E-05
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	6,60E-02	1,11E-04	7,00E-04	3,48E-02	2,91E-04	-1,03E-03
Global Warming Potential (GWP 100 years) [kg CO2 eq.]	6,29E-01	7,01E-02	1,19E-01	5,52E+00	7,62E-02	1,56E+00
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	1,30E-01	2,46E-03	2,92E-03	1,88E-01	2,53E-03	-3,88E-02
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	1,83E+02	4,14E+00	1,54E+00	9,60E+01	7,06E+00	-2,49E+02
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	1,99E-08	1,32E-11	5,49E-13	4,16E-12	7,89E-13	-2,74E-08
Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	5,03E-04	1,23E-05	-8,01E-05	7,48E-04	2,11E-05	-9,92E-05
Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	1,11E-03	3,07E-05	2,71E-04	2,76E-03	1,13E-03	-1,81E-04
Primary energy demand [MJ]	3,77E+01	1,61E+00	1,86E+00	1,04E+02	1,44E+00	-8,92E+00
Total water consumption [kg]	2,36E-02	2,30E-03	1,43E-04	1,21E-02	1,37E-03	-5,78E-03

F.1.3 BRAKE PEDAL

Table F.5 - LCIA Results for brake pedal project [standard design].

	BRAKE PEDAL					
	Standard design *[ferrous insert + plastic co-molded part]*					
Impact categories	Materials	Logistic	Manufacturing	Use	EoL (W)	EoL (B)
Abiotic Depletion (ADP elements) [kg Sb eq.]	1,23E-04	6,41E-09	1,37E-07	5,38E-07	-8,78E-06	-8,90E-06
Abiotic Depletion (ADP fossil) [MJ]	7,68E+01	1,09E+00	2,47E+00	1,14E+02	-1,92E+00	-8,58E+00
Acidification Potential (AP) [kg SO2 eq.]	3,20E-02	1,99E-04	4,34E-04	6,65E-03	-1,50E-03	-1,01E-03
Eutrophication Potential (EP) [kg Phosphate eq.]	3,17E-03	4,80E-05	4,76E-05	1,07E-03	2,53E-05	1,53E-04
Freshwater Aquatic Ecotox. (FAETP) [kg DCB eq.]	4,27E-02	4,32E-04	2,86E-04	4,29E-02	-1,21E-03	-1,70E-03
Global Warming Potential (GWP) [kg CO2 eq.]	6,41E+00	7,92E-02	1,98E-01	6,81E+00	-2,20E-01	2,50E-01
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	1,08E+00	1,63E-03	7,33E-03	2,33E-01	-5,13E-02	-5,73E-02
Marine Aquatic Ecotoxicity (MAETP) [kg DCB eq.]	2,71E+03	1,04E+00	1,51E+01	1,19E+02	-2,04E+02	-2,21E+02
Ozone Layer Depletion Potential (ODP) [kg R11 eq.]	1,38E-07	2,65E-14	7,42E-12	5,18E-12	-1,13E-08	-1,13E-08
Photochemical. Ozone Creation (POCP) [kg Ethene eq.]	2,18E-03	-6,7E-05	3,20E-05	9,24E-04	-9,90E-05	-1,13E-04
Terrestric Ecotoxicity Poten (TETP inf.) [kg DCB eq.]	1,39E-01	1,31E-04	2,87E-05	3,45E-03	-1,04E-02	-1,12E-02
Primary energy demand [MJ]	9,51E+01	1,23E+00	4,98E+00	1,29E+02	-2,38E+00	-1,19E+01
Total freshwater consumption [kg]	4,46E-02	9,47E-05	6,96E-03	1,51E-02	8,82E-04	-5,21E-03

Table F.6 - LCIA Results for brake pedal project [innovative design].

	BRAKE PEDAL					
	Innovative design *[one unitary structure of plastic part]*					
Impact categories	Materials	Logistic	Manufacturing	Use	EoL (W)	EOL (B)
Abiotic Depletion (ADP elements) [kg Sb eq.]	6,93E-06	6,30E-09	1,32E-07	2,93E-07	1,58E-08	-1,65E-07
Abiotic Depletion (ADP fossil) [MJ]	9,13E+01	1,07E+00	2,37E+00	6,19E+01	7,06E-01	-8,18E+00
Acidification Potential (AP) [kg SO2 eq.]	8,04E-03	1,96E-04	4,16E-04	3,62E-03	1,34E-04	1,37E-03
Eutrophication Potential (EP) [kg Phosphate eq.]	1,21E-03	4,72E-05	4,57E-05	5,80E-04	1,11E-04	4,54E-04
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	2,03E-02	4,25E-04	2,75E-04	2,33E-02	1,97E-04	-3,38E-04
Global Warming Potential (GWP 100 years) [kg CO2 eq.]	5,36E+00	7,79E-02	1,90E-01	3,70E+00	5,13E-02	5,76E-01
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	5,44E-01	1,61E-03	7,03E-03	1,27E-01	1,70E-03	-1,44E-03
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	2,04E+02	1,03E+00	1,45E+01	6,45E+01	4,76E+00	-1,33E+01
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	8,12E-12	2,61E-14	7,12E-12	2,82E-12	5,15E-13	2,46E-09
Photochemical. Ozone Creation Potential (POCP) [kg Ethene eq.]	1,11E-03	-6,62E-05	3,08E-05	5,03E-04	1,43E-05	2,45E-05
Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	1,55E-03	1,29E-04	2,76E-05	1,88E-03	7,69E-04	-3,46E-06
Primary energy demand [MJ]	1,11E+02	1,21E+00	4,78E+00	7,00E+01	9,66E-01	-1,13E+01
Total freshwater consumption (including rainwater) [kg]	1,43E-01	9,32E-05	6,68E-03	8,23E-03	9,09E-04	-6,91E-03

F.1.4 DASHBOARD

Table F.7 - LCIA Results for dashboard project [standard design].

	DASHBOARD					
	Standard design *[PP+talcum]*					
Impact categories	Materials	Manufacturing	Logistic	Use	EoL (W)	EoL (B)
Abiotic Depletion (ADP elements) [kg Sb eq.]	3,15E-05	1,01E-06	1,15E-08	2,46E-06	7,49E-08	1,47E-06
Abiotic Depletion (ADP fossil) [MJ]	3,37E+02	5,09E+01	4,04E+00	4,05E+02	5,01E+00	4,85E+00
Acidification Potential (AP) [kg SO2 eq.]	2,64E-02	9,97E-03	7,53E-04	1,73E-02	9,75E-04	2,83E-03
Eutrophication Potential (EP) [kg Phosphate eq.]	6,39E-03	1,18E-03	1,86E-04	3,51E-03	9,31E-04	2,37E-04
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	7,97E-02	7,98E-03	2,04E-03	1,63E-01	1,58E-03	8,44E-04
Global Warming Potential (GWP 100 years) [kg CO2 eq.]	1,08E+01	3,93E+00	2,93E-01	1,55E+01	3,58E-01	1,20E+01
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	1,48E+00	1,59E-01	9,68E-03	6,11E-01	1,16E-02	2,03E-01
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	5,51E+02	2,32E+02	4,03E+00	3,89E+02	3,51E+01	2,87E+01
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	1,96E-08	8,10E-10	1,21E-12	8,12E-13	1,44E-12	1,57E-12
Photochemical. Ozone Creation Potential (POCP) [kg Ethene eq.]	3,86E-03	8,39E-04	-2,04E-04	2,75E-03	1,09E-04	1,31E-04
Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	9,39E-03	6,63E-03	2,18E-03	5,34E-02	6,59E-03	1,73E-03
Primary energy demand [MJ]	3,90E+02	8,09E+01	4,58E+00	4,58E+02	6,22E+00	7,28E+00

Table F.8 - LCIA Results for dashboard project [innovative design].

	DASHBOARD					
	Innovative design *[PP+HGM]*					
Impact categories	Materials	Manufacturing	Logistic	Use	EoL (W)	EOL (B)
Abiotic Depletion (ADP elements) [kg Sb eq.]	7,11E-05	7,68E-07	7,51E-07	2,07E-06	6,25E-08	1,22E-06
Abiotic Depletion (ADP fossil) [MJ]	3,19E+02	3,88E+01	9,97E+01	3,39E+02	4,18E+00	4,05E+00
Acidification Potential (AP) [kg SO2 eq.]	2,89E-02	7,61E-03	4,95E-03	1,45E-02	8,15E-04	2,37E-03
Eutrophication Potential (EP) [kg Phosphate eq.]	6,73E-03	9,80E-04	6,00E-04	2,95E-03	7,78E-04	1,98E-04
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	7,19E-02	6,17E-03	3,02E-02	1,36E-01	1,32E-03	7,05E-04
Global Warming Potential (GWP 100 years) [kg CO2 eq.]	1,07E+01	2,99E+00	2,75E+00	1,30E+01	2,99E-01	1,00E+01
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	1,46E+00	1,21E-01	1,07E-01	5,13E-01	9,72E-03	1,69E-01
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	5,50E+02	1,79E+02	1,22E+02	3,26E+02	2,93E+01	2,40E+01
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	1,93E-08	6,12E-10	5,49E-11	6,82E-13	1,20E-12	1,31E-12
Photochemical. Ozone Creation Potential (POCP) [kg Ethene eq.]	2,76E-03	6,44E-04	7,31E-04	2,31E-03	9,13E-05	1,09E-04
Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	9,16E-03	5,67E-03	3,32E-03	4,48E-02	5,50E-03	1,44E-03
Primary energy demand [MJ]	3,69E+02	6,15E+01	1,13E+02	3,84E+02	5,19E+00	6,08E+00

F.1.5 SUSPENSION ARM

Table F.9 - LCIA Results for suspension arm project [standard design].

	SUSPENSION ARM				
	Standard design [Steel]				
Impact categories	Materials	Logistic	Manufacturing	Use	EoL
Abiotic Depletion (ADP elements) [kg Sb eq.]	-2,13E-07	3,22E-09	1,03E-06	8,39E-07	1,20E-09
Abiotic Depletion (ADP fossil) [MJ]	1,52E+00	1,20E+00	2,50E+01	3,79E+02	-2,39E+01
Acidification Potential (AP) [kg SO2 eq.]	1,89E-02	2,20E-04	3,93E-03	3,83E-02	-1,57E-03
Eutrophication Potential (EP) [kg Phosphate eq.]	1,36E-03	4,54E-05	4,65E-04	4,10E-03	-2,86E-04
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	7,41E-03	2,03E-04	3,00E-03	3,41E-02	-6,59E-04
Global Warming Potential (GWP 100 years) [kg CO2 eq.]	8,72E+00	8,63E-02	1,61E+00	2,85E+01	-5,43E-01
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	2,54E-01	1,86E-03	4,89E-02	5,17E-01	-2,43E-03
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	1,18E+03	6,40E-01	1,37E+02	2,28E+02	4,26E+00
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	4,38E-08	1,51E-12	9,26E-10	4,81E-10	-1,02E-11
Photochemical. Ozone Creation Potential (POCP) [kg Ethene eq.]	3,90E-03	-5,49E-05	3,84E-04	1,10E-02	-1,54E-04
Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	1,11E-02	6,36E-04	4,48E-03	4,19E-02	-8,26E-05
Primary energy demand [MJ]	2,60E+00	1,33E+00	3,08E+01	4,22E+02	-2,47E+01

Table F.10 - LCIA Results for crossmember project [first innovative design].

	SUSPENSION ARM				
	Innovative design A [primary Al. + GF composite]				
Impact categories	Materials	Logistic	Manufacturing	Use	EoL
Abiotic Depletion (ADP elements) [kg Sb eq.]	1,10E-04	2,17E-09	6,47E-07	4,82E-07	2,06E-08
Abiotic Depletion (ADP fossil) [MJ]	1,47E+02	8,07E-01	1,57E+01	2,18E+02	1,63E+00
Acidification Potential (AP) [kg SO2 eq.]	3,38E-02	1,46E-04	3,32E-03	2,20E-02	-2,48E-05
Eutrophication Potential (EP) [kg Phosphate eq.]	3,46E-03	2,99E-05	2,55E-04	2,36E-03	2,59E-04
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	1,84E-02	1,37E-04	1,06E-02	1,96E-02	3,60E-04
Global Warming Potential (GWP 100 years) [kg CO2 eq.]	1,10E+01	5,82E-02	1,28E+00	1,64E+01	1,08E-01
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	2,39E+00	1,26E-03	7,20E-02	2,97E-01	3,74E-03
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	6,83E+03	4,32E-01	1,83E+02	1,31E+02	1,27E+01
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	1,61E-09	1,02E-12	3,20E-09	2,76E-10	6,52E-11
Photochemical. Ozone Creation Potential (POCP) [kg Ethene eq.]	6,46E-03	-3,58E-05	2,74E-04	6,30E-03	2,06E-05
Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	2,87E-01	4,29E-04	4,17E-03	2,41E-02	1,96E-03
Primary energy demand [MJ]	1,73E+02	8,97E-01	2,05E+01	2,42E+02	1,94E+00

Table F.11 - LCIA Results for suspension arm project [second innovative design].

	SUSPENSION ARM				
	Innovative design B [steel. + GF composite]				
Impact categories	Materials	Logistic	Manufacturing	Use	EoL
Abiotic Depletion (ADP elements) [kg Sb eq.]	1,09E-04	2,51E-09	1,70E-07	5,76E-07	2,11E-08
Abiotic Depletion (ADP fossil) [MJ]	1,09E+02	9,34E-01	1,61E+01	2,60E+02	-3,11E+00
Acidification Potential (AP) [kg SO2 eq.]	2,12E-02	1,69E-04	3,16E-03	2,63E-02	-1,63E-05
Eutrophication Potential (EP) [kg Phosphate eq.]	2,94E-03	3,47E-05	2,21E-04	2,82E-03	2,37E-04
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	1,07E-02	1,58E-04	1,66E-03	2,34E-02	2,53E-04
Global Warming Potential (GWP 100 years) [kg CO2 eq.]	9,39E+00	6,74E-02	1,25E+00	1,96E+01	5,69E-03
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	2,14E-01	1,45E-03	3,93E-02	3,55E-01	3,99E-03
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	3,54E+02	5,00E-01	6,81E+01	1,57E+02	1,31E+01
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	8,87E-09	1,18E-12	6,49E-10	3,30E-10	5,96E-11
Photochemical. Ozone Creation Potential (POCP) [kg Ethene eq.]	6,00E-03	-4,15E-05	2,62E-04	7,53E-03	9,75E-06
Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	2,75E-01	4,97E-04	3,44E-03	2,88E-02	1,95E-03
Primary energy demand [MJ]	1,21E+02	1,04E+00	2,11E+01	2,89E+02	-2,98E+00

Table F.12 - LCIA Results for suspension arm project [third innovative design].

	SUSPENSION ARM				
	Innovativi design C [secondary Al. + GF composite]				
Impact categories	Materials	Logistic	Manufacturing	Use	EoL
Abiotic Depletion (ADP elements) [kg Sb eq.]	1,09E-04	2,17E-09	6,47E-07	4,82E-07	2,06E-08
Abiotic Depletion (ADP fossil) [MJ]	1,10E+02	8,07E-01	1,57E+01	2,18E+02	1,63E+00
Acidification Potential (AP) [kg SO2 eq.]	1,85E-02	1,46E-04	3,32E-03	2,20E-02	-2,48E-05
Eutrophication Potential (EP) [kg Phosphate eq.]	2,75E-03	2,99E-05	2,55E-04	2,36E-03	2,59E-04
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	9,90E-03	1,37E-04	1,06E-02	1,96E-02	3,60E-04
Global Warming Potential (GWP 100 years) [kg CO2 eq.]	8,18E+00	5,82E-02	1,28E+00	1,64E+01	1,08E-01
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	1,79E-01	1,26E-03	7,20E-02	2,97E-01	3,74E-03
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	1,98E+02	4,32E-01	1,83E+02	1,31E+02	1,27E+01
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	7,91E-09	1,02E-12	3,20E-09	2,76E-10	6,52E-11
Photochemical. Ozone Creation Potential (POCP) [kg Ethene eq.]	5,44E-03	-3,58E-05	2,74E-04	6,30E-03	2,06E-05
Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	2,74E-01	4,29E-04	4,17E-03	2,41E-02	1,96E-03
Primary energy demand [MJ]	1,22E+02	8,97E-01	2,05E+01	2,42E+02	1,94E+00

Table F.13 - LCIA Results for suspension arm project [third innovative design].

	SUSPENSION ARM				
	Innovative design D [steel + CF composite]				
Impact categories	Materials	Logistic	Manufacturing	Use	EoL
Abiotic Depletion (ADP elements) [kg Sb eq.]	4,43E-06	2,11E-09	1,70E-07	4,87E-07	1,65E-08
Abiotic Depletion (ADP fossil) [MJ]	2,29E+02	7,84E-01	1,61E+01	2,20E+02	-3,48E+00
Acidification Potential (AP) [kg SO2 eq.]	2,65E-02	1,42E-04	3,16E-03	2,22E-02	-8,22E-05
Eutrophication Potential (EP) [kg Phosphate eq.]	4,03E-03	2,91E-05	2,21E-04	2,38E-03	1,72E-04
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	2,14E-02	1,33E-04	1,66E-03	1,98E-02	1,68E-04
Global Warming Potential (GWP 100 years) [kg CO2 eq.]	1,52E+01	5,66E-02	1,25E+00	1,65E+01	-1,96E-02
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	3,81E-01	1,22E-03	3,93E-02	3,00E-01	3,01E-03
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	8,47E+02	4,20E-01	6,81E+01	1,33E+02	1,04E+01
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	1,11E-08	9,88E-13	6,49E-10	2,79E-10	4,61E-11
Photochemical. Ozone Creation Potential (POCP) [kg Ethene eq.]	4,21E-03	-3,49E-05	2,62E-04	6,36E-03	8,00E-07
Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	3,31E-01	4,17E-04	3,44E-03	2,43E-02	1,52E-03
Primary energy demand [MJ]	2,62E+02	8,71E-01	2,11E+01	2,45E+02	-3,42E+00

F.1.6 THROTTLE BODY

Table F.14 - LCIA Results for throttle body project [standard design].

THROTTLE BODY						
Standard Design [Aluminum-housing]						
Impact categories	Materials	Logistic	Manufacturing	Use	EoL (W)	EoL (B)
Abiotic Depletion (ADP elements) [kg Sb eq.]	5,36E-05	3,88E-09	1,23E-07	4,51E-07	-1,29E-07	-1,19E-06
Abiotic Depletion (ADP fossil) [MJ]	2,52E+01	1,40E+00	7,05E+00	9,53E+01	-2,39E+00	-2,68E+01
Acidification Potential (AP) [kg SO2 eq.]	7,07E-03	1,92E-03	2,72E-03	5,57E-03	-1,31E-03	-1,24E-02
Eutrophication Potential (EP) [kg Phosphate eq.]	4,71E-04	2,14E-04	1,43E-04	8,93E-04	-5,30E-05	-7,13E-04
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	1,48E-02	6,19E-04	1,65E-03	3,59E-02	-2,49E-03	-1,72E-02
Global Warming Potential (GWP 100 years) [kg CO2 eq.]	1,70E+00	1,09E-01	5,26E-01	7,14E+00	-2,29E-01	-2,30E+00
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	8,28E-01	4,32E-03	3,34E-02	1,95E-01	-2,10E+00	-1,16E+01
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	5,35E+02	1,43E+00	5,05E+01	9,93E+01	-5,61E+02	-5,65E+03
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	2,53E-08	2,56E-13	5,60E-11	4,34E-12	-7,27E-09	-2,36E-11
Photochemical. Ozone Creation Potential (POCP) [kg Ethene eq.]	4,93E-04	7,00E-05	1,77E-04	7,74E-04	-7,79E-05	-6,96E-04
Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	3,61E-02	3,73E-04	7,84E-04	2,89E-03	-5,04E-04	-5,66E-03
Primary energy demand [MJ]	3,36E+01	1,55E+00	1,30E+01	1,08E+02	-4,13E+00	-4,69E+01

Table F.15 - LCIA Results for throttle body project [innovative design].

THROTTLE BODY						
Innovative Design [Plastic-housing]						
Impact categories	Materials	Logistic	Manufacturing	Use	EoL (W)	EoL (B)
Abiotic Depletion (ADP elements) [kg Sb eq.]	6,42E-05	4,40E-09	4,35E-08	3,55E-07	1,58E-08	-4,44E-07
Abiotic Depletion (ADP fossil) [MJ]	3,62E+01	1,59E+00	2,22E+00	7,51E+01	7,06E-01	-1,18E+01
Acidification Potential (AP) [kg SO2 eq.]	1,19E-02	1,96E-03	8,73E-04	4,39E-03	1,34E-04	-5,37E-03
Eutrophication Potential (EP) [kg Phosphate eq.]	7,50E-04	2,23E-04	4,88E-05	7,04E-04	1,11E-04	-3,08E-04
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	1,88E-02	7,13E-04	5,43E-04	2,83E-02	1,97E-04	-7,54E-03
Global Warming Potential (GWP 100 years) [kg CO2 eq.]	2,50E+00	1,23E-01	1,87E-01	5,63E+00	5,13E-02	-4,03E-01
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	3,14E+00	4,77E-03	1,11E-02	1,54E-01	1,70E-03	-5,07E+00
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	1,47E+03	1,61E+00	1,68E+01	7,83E+01	4,76E+00	-2,47E+03
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	4,89E-08	3,11E-13	2,55E-11	3,42E-12	5,15E-13	-1,04E-11
Photochemical. Ozone Creation Potential (POCP) [kg Ethene eq.]	9,33E-04	6,00E-05	5,71E-05	6,10E-04	1,43E-05	-3,11E-04
Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	3,83E-02	4,73E-04	2,63E-04	2,28E-03	7,69E-04	-2,56E-03
Primary energy demand [MJ]	5,01E+01	1,76E+00	4,20E+00	8,50E+01	9,66E-01	-2,04E+01

F.1.7 HEADLAMP REFLECTOR

Table F.16 - LCIA Results for headlamp reflector project [standard design].

	HEADLAMP REFLECTOR				
	Thermoset - BMC				
Impact categories	Materials	Logistic	Manufacturing	Use	EoL
Abiotic Depletion (ADP elements) [kg Sb eq.]	1,13E-05	7,89E-10	2,62E-06	2,05E-07	1,18E-07
Abiotic Depletion (ADP fossil) [MJ]	1,80E+01	2,93E-01	2,83E+01	4,22E+01	3,90E-01
Acidification Potential (AP) [kg SO2 eq.]	2,51E-03	5,25E-05	1,08E-02	2,29E-03	2,28E-04
Eutrophication Potential (EP) [kg Phosphate eq.]	2,81E-04	1,07E-05	5,87E-04	4,07E-04	1,90E-05
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	1,52E-03	4,97E-05	3,11E-03	1,60E-02	6,78E-05
Global Warming Potential (GWP 100 years) [kg CO2 eq.]	1,06E+00	2,11E-02	2,24E+00	2,63E+00	9,62E-01
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	2,11E-02	4,56E-04	7,59E-02	9,40E-02	1,63E-02
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	5,59E+01	1,57E-01	1,17E+02	4,38E+01	2,31E+00
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	2,45E-10	3,70E-13	3,32E-10	1,17E-13	1,26E-13
Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	7,09E-04	-1,27E-05	6,59E-04	3,41E-04	1,05E-05
Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	8,36E-04	1,56E-04	5,83E-03	1,31E-03	1,39E-04
Primary energy demand [MJ]	2,07E+01	3,26E-01	3,23E+01	4,78E+01	5,85E-01

Table F.17 - LCIA Results for headlamp reflector project [innovative design].

	HEADLAMP REFLECTOR				
	Thermoplastic - PES				
Impact categories	Materials	Logistic	Manufacturing	Use	EoL
Abiotic Depletion (ADP elements) [kg Sb eq.]	2,29E-05	3,61E-10	1,14E-06	1,35E-07	7,75E-08
Abiotic Depletion (ADP fossil) [MJ]	7,79E+01	1,34E-01	8,24E+00	2,78E+01	2,57E-01
Acidification Potential (AP) [kg SO2 eq.]	7,72E-03	2,37E-05	1,30E-03	1,50E-03	1,50E-04
Eutrophication Potential (EP) [kg Phosphate eq.]	1,02E-03	4,80E-06	1,43E-04	2,68E-04	1,25E-05
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	4,54E-03	2,27E-05	1,05E-03	1,05E-02	4,46E-05
Global Warming Potential (GWP 100 years) [kg CO2 eq.]	4,17E+00	9,69E-03	7,72E-01	1,73E+00	6,33E-01
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	7,05E-02	2,09E-04	2,41E-02	6,19E-02	1,07E-02
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	1,76E+02	7,19E-02	6,71E+01	2,88E+01	1,52E+00
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	7,62E-10	1,69E-13	4,06E-10	7,69E-14	8,30E-14
Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	9,53E-04	-5,62E-06	9,20E-05	2,24E-04	6,90E-06
Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	2,75E-03	7,14E-05	2,62E-03	8,59E-04	9,12E-05
Primary energy demand [MJ]	8,85E+01	1,49E-01	1,03E+01	3,15E+01	3,85E-01

E.1.8 CROSSMEMBER

Table F.18 - LCIA Results for crossmember project [standard design].

CROSSMEMBER					
Standard Design [steel]					
Impact categories	Materials	Logistic	Manufacturing	Use	EoL
Abiotic Depletion (ADP elements) [kg Sb eq.]	7,46E-03	6,06E-08	1,84E-04	8,19E-06	4,72E-07
Abiotic Depletion (ADP fossil) [MJ]	1,72E+03	1,25E+01	4,37E+03	1,96E+03	1,08E+01
Acidification Potential (AP) [kg SO2 eq.]	1,13E+00	2,21E-03	6,92E-01	1,60E-01	1,62E-03
Eutrophication Potential (EP) [kg Phosphate eq.]	5,41E-02	5,12E-04	7,03E-02	1,85E-02	2,17E-04
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	2,74E+00	5,34E-03	5,43E-01	7,36E-01	1,42E-03
Global Warming Potential (GWP 100 years) [kg CO2 eq.]	1,50E+02	9,10E-01	3,47E+02	1,36E+02	9,83E-01
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	1,52E+02	2,23E-02	1,21E+01	4,48E+00	4,85E-02
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	1,16E+05	1,17E+01	2,07E+04	1,99E+03	9,24E+01
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	6,48E-06	4,18E-12	6,45E-08	1,02E-09	1,04E-10
Photochemical. Ozone Creation Potential (POCP) [kg Ethene eq.]	7,38E-02	-6,13E-04	6,03E-02	2,51E-02	1,29E-04
Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	6,09E+00	2,06E-03	1,54E-01	7,73E-02	6,24E-04
Primary energy demand [MJ]	2,26E+03	1,42E+01	7,89E+03	2,21E+03	2,01E+01

Table F.19 - LCIA Results for crossmember project [first innovative design].

CROSSMEMBER					
First Innovative Design [aluminum]					
Impact categories	Materials	Logistic	Manufacturing	Use	EoL
Abiotic Depletion (ADP elements) [kg Sb eq.]	6,98E-05	1,57E-07	8,40E-08	6,74E-06	4,83E-07
Abiotic Depletion (ADP fossil) [MJ]	1,49E+03	3,25E+01	2,05E+01	1,60E+03	1,11E+01
Acidification Potential (AP) [kg SO2 eq.]	6,87E-01	5,71E-03	7,28E-03	1,32E-01	1,69E-03
Eutrophication Potential (EP) [kg Phosphate eq.]	3,91E-02	1,32E-03	5,55E-04	1,53E-02	2,14E-04
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	9,89E-01	1,38E-02	1,61E-03	6,05E-01	1,45E-03
Global Warming Potential (GWP 100 years) [kg CO2 eq.]	1,38E+02	2,36E+00	2,14E+00	1,12E+02	9,85E-01
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	6,70E+02	5,77E-02	8,74E-02	3,70E+00	4,60E-02
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	3,24E+05	3,04E+01	2,53E+02	1,64E+03	8,62E+01
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	4,22E-08	1,08E-11	3,79E-12	8,41E-10	1,19E-10
Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	4,08E-02	-1,58E-03	5,05E-04	2,07E-02	1,38E-04
Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	3,07E-01	5,35E-03	1,80E-03	6,36E-02	5,89E-04
Primary energy demand [MJ]	2,66E+03	3,68E+01	2,50E+01	1,82E+03	2,06E+01

Table F.20 - LCIA Results for crossmember project [second innovative design].

CROSSMEMBER						
Second Innovative Design [plastic]						
Impact categories	Materials	Logistic	Manufacturing	Use	EoL (W)	EoL (B)
Abiotic Depletion (ADP elements) [kg Sb eq.]	7,17E-05	5,10E-08	3,21E-06	3,17E-06	3,79E-07	-1,94E-07
Abiotic Depletion (ADP fossil) [MJ]	2,09E+03	1,06E+01	7,65E+01	7,55E+02	1,53E+01	-1,16E+02
Acidification Potential (AP) [kg SO2 eq.]	2,25E-01	1,86E-03	1,21E-02	6,20E-02	2,71E-03	-3,67E-02
Eutrophication Potential (EP) [kg Phosphate eq.]	3,88E-02	4,29E-04	1,23E-03	7,22E-03	1,95E-03	7,42E-03
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	4,04E-01	4,50E-03	9,51E-03	2,85E-01	3,83E-03	-3,67E-02
Global Warming Potential (GWP 100 years) [kg CO2 eq.]	1,26E+02	7,66E-01	6,07E+00	5,29E+01	1,18E+00	1,10E+01
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	3,85E+00	1,87E-02	2,12E-01	1,74E+00	4,69E-02	-1,36E+00
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	8,69E+03	9,89E+00	3,62E+02	7,71E+02	1,13E+02	-9,73E+03
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	1,45E-08	3,52E-12	1,13E-09	3,96E-10	8,20E-11	-1,31E-06
Photochemical. Ozone Creation Potential (POCP) [kg Ethene eq.]	3,24E-02	-5,14E-04	1,05E-03	9,76E-03	3,10E-04	-1,67E-03
Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	8,11E-02	1,74E-03	2,69E-03	3,00E-02	1,34E-02	-1,23E-02
Primary energy demand [MJ]	2,87E+03	1,20E+01	1,38E+02	8,57E+02	2,21E+01	-1,89E+02

F.2 STRATEGY 2

F.2.1 MUFFLER

Table F.21 - LCIA Results for muffler project [standard design].

	MUFFLER					
	Standard design *[Rolled]*					
Impact categories	Materials	Logistic	Manufacturing	Use	EoL (W)	EoL (B)
Abiotic Depletion (ADP elements) [kg Sb eq.]	4,52E-04	2,77E-09	8,84E-08	1,94E-06	1,16E-08	5,27E-08
Abiotic Depletion (ADP fossil) [MJ]	1,56E+02	1,01E+00	8,78E+00	4,01E+02	-1,91E+01	-1,91E+01
Acidification Potential (AP) [kg SO2 eq.]	8,51E-02	3,36E-04	1,83E-03	2,17E-02	-7,05E-03	-6,99E-03
Eutrophication Potential (EP) [kg Phosphate eq.]	4,87E-03	7,67E-05	1,32E-04	3,86E-03	-5,45E-04	-5,65E-04
Freshwater Aquatic Ecotoxicity (FAETP) [kg DCB eq.]	5,25E-02	5,19E-04	1,35E-03	1,52E-01	-3,99E-03	-4,01E-03
Global Warming Potential (GWP 100) [kg CO2 eq.]	1,57E+01	7,34E-02	6,72E-01	2,30E+01	-1,96E+00	-1,62E+00
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	2,00E+00	2,31E-03	2,20E-02	8,93E-01	-2,38E-01	-2,33E-01
Marine Aquatic Ecotoxicity (MAETP) [kg DCB eq.]	1,03E+04	9,85E-01	3,48E+01	4,17E+02	-1,60E+02	-1,61E+02
Ozone Layer Depletion Potential (ODP,) [kg R11 eq.]	5,56E-07	3,51E-16	1,13E-10	1,11E-12	-6,81E-12	-6,80E-12
Photochemical. Ozone Creation (POCP) [kg Ethene eq.]	6,34E-03	-1,08E-04	1,46E-04	3,24E-03	-9,73E-04	-9,72E-04
Terrestric Ecotoxicity Potential (TETP) [kg DCB eq.]	5,41E-01	5,32E-04	5,99E-04	1,24E-02	-1,18E-02	-1,19E-02
Primary energy demand [MJ]	2,00E+02	1,13E+00	1,29E+01	4,54E+02	-2,01E+01	-2,01E+01

Table F.22 - LCIA Results for muffler project [innovative design].

	MUFFLER					
	Innovative design *[Stamped]*					
Impact categories	Materials	Logistic	Manufacturing	Use	EoL (W)	EOL (B)
Abiotic Depletion (ADP elements) [kg Sb eq.]	4,50E-05	2,97E-09	5,90E-08	1,90E-06	1,14E-08	5,25E-08
Abiotic Depletion (ADP fossil) [MJ]	1,66E+02	1,09E+00	5,86E+00	3,92E+02	-1,87E+01	-1,87E+01
Acidification Potential (AP) [kg SO2 eq.]	8,69E-02	3,62E-04	1,22E-03	2,12E-02	-6,89E-03	-6,83E-03
Eutrophication Potential (EP) [kg Phosphate eq.]	5,00E-03	8,27E-05	8,78E-05	3,78E-03	-5,31E-04	-5,52E-04
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	5,29E-02	5,58E-04	9,05E-04	1,48E-01	-3,89E-03	-3,92E-03
Global Warming Potential (GWP 100 years) [kg CO2 eq.]	1,68E+01	7,89E-02	4,49E-01	2,25E+01	-1,92E+00	-1,57E+00
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	2,01E+00	2,50E-03	1,47E-02	8,74E-01	-2,33E-01	-2,27E-01
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	1,04E+04	1,06E+00	2,23E+01	4,07E+02	-1,57E+02	-1,57E+02
Ozone Layer Depletion Potential (ODP) [kg R11 eq.]	5,60E-07	3,78E-13	7,56E-11	1,09E-12	-6,65E-12	-6,65E-12
Photochemical. Ozone Creation Potential (POCP) [kg Ethene eq.]	6,64E-03	-1,17E-04	9,75E-05	3,16E-03	-9,51E-04	-9,50E-04
Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	5,38E-01	5,71E-04	4,00E-04	1,21E-02	-1,15E-02	-1,16E-02
Primary energy demand [MJ]	2,11E+02	1,21E+00	8,59E+00	4,44E+02	-1,97E+01	-1,96E+01

F.2.2 FUEL TANK

Table F.23 - LCIA Results for fuel tank project [standard design].

	FUEL TANK					
	Standard design *[Blowmolding]*					
Impact categories	Materials	Logistic	Manufacturing	Use	EoL (W)	EoL (B)
Abiotic Depletion (ADP elements) [kg Sb eq.]	5,54E-06	2,41E-08	3,44E-07	3,77E-06	1,11E-07	2,17E-06
Abiotic Depletion (ADP fossil) [MJ]	5,45E+02	8,81E+00	3,42E+01	7,78E+02	7,41E+00	7,18E+00
Acidification Potential (AP) [kg SO2 eq.]	3,24E-02	1,57E-03	7,12E-03	4,21E-02	1,44E-03	4,19E-03
Eutrophication Potential (EP) [kg Phosphate eq.]	2,57E-03	3,12E-04	5,12E-04	7,49E-03	1,38E-03	3,51E-04
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	1,84E-01	4,52E-03	5,28E-03	2,94E-01	2,33E-03	1,25E-03
Global Warming Potential (GWP 100 years) [kg CO2 eq.]	1,43E+01	6,39E-01	2,62E+00	3,70E+01	5,29E-01	1,77E+01
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	4,98E-01	1,90E-02	8,58E-02	1,73E+00	1,72E-02	3,00E-01
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	6,53E+02	8,57E+00	1,36E+02	8,08E+02	5,19E+01	4,25E+01
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	2,03E-10	3,06E-12	4,41E-10	2,15E-12	2,13E-12	2,32E-12
Photochemical. Ozone Creation Potential (POCP) [kg Ethene eq.]	8,38E-03	-3,46E-04	5,69E-04	6,27E-03	1,62E-04	1,93E-04
Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	7,75E-03	4,63E-03	2,33E-03	2,40E-02	9,75E-03	2,55E-03
Primary energy demand [MJ]	6,12E+02	9,84E+00	5,01E+01	8,81E+02	9,20E+00	1,08E+01

Table F.24 - LCIA Results for fuel tank project [innovative design].

	FUEL TANK					
	Innovative design *[2 shells injected]*					
Impact categories	Materials	Logistic	Manufacturing	Use	EoL (W)	EOL (B)
Abiotic Depletion (ADP elements) [kg Sb eq.]	9,14E-06	1,43E-08	5,71E-07	2,54E-06	7,47E-08	1,46E-06
Abiotic Depletion (ADP fossil) [MJ]	4,09E+02	5,24E+00	5,67E+01	5,24E+02	4,99E+00	4,84E+00
Acidification Potential (AP) [kg SO2 eq.]	2,62E-02	9,33E-04	1,18E-02	2,84E-02	9,72E-04	2,83E-03
Eutrophication Potential (EP) [kg Phosphate eq.]	2,84E-03	1,86E-04	8,50E-04	5,05E-03	9,28E-04	2,36E-04
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	1,11E-01	2,69E-03	8,76E-03	1,98E-01	1,57E-03	8,41E-04
Global Warming Potential (GWP 100 years) [kg CO2 eq.]	1,46E+01	3,80E-01	4,35E+00	2,49E+01	3,57E-01	1,19E+01
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	3,57E-01	1,13E-02	1,42E-01	1,17E+00	1,16E-02	2,02E-01
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	5,72E+02	5,10E+00	2,25E+02	5,44E+02	3,49E+01	2,86E+01
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	2,06E-10	1,82E-12	7,32E-10	1,45E-12	1,44E-12	1,57E-12
Photochemical. Ozone Creation Potential (POCP) [kg Ethene eq.]	8,16E-03	-2,06E-04	9,44E-04	4,22E-03	1,09E-04	1,30E-04
Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	7,53E-03	2,75E-03	3,87E-03	1,62E-02	6,57E-03	1,72E-03
Primary energy demand [MJ]	4,65E+02	5,85E+00	8,31E+01	5,93E+02	6,20E+00	7,25E+00

F.3 STRATEGY 3

Table F.25 – LCIA Results for auxiliary module project.

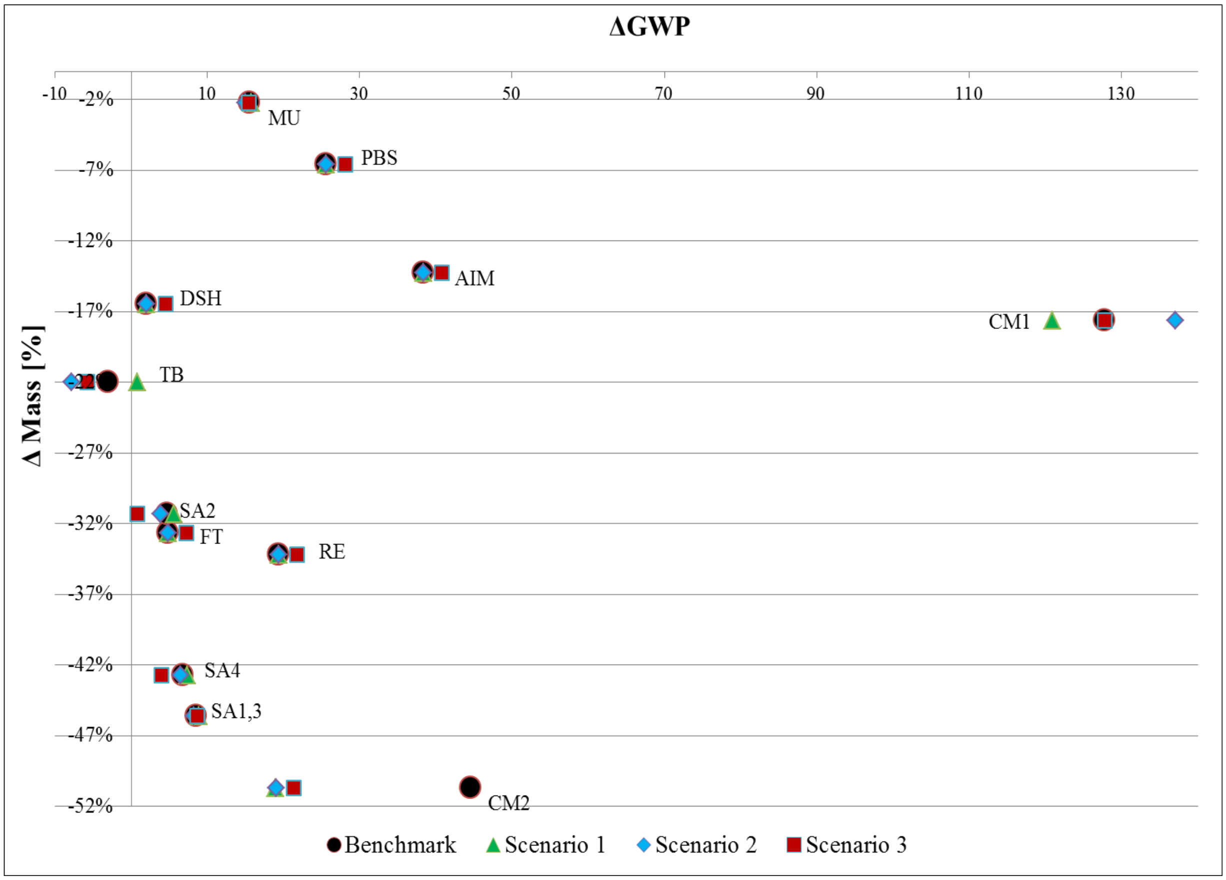
	AUXILIARY MODULE					
	Standard design [Halogen technology]			**Innovative design** [LED technology]		
Impact categories	Production (materials and manufacturing)	Use	EoL	Production (materials and manufacturing)	Use	EoL
Abiotic Depletion (ADP elements) [kg Sb eq.]	8,94E-04	5,44E-06	-7,85E-08	8,21E-06	2,90E-06	-4,66E-07
Abiotic Depletion (ADP fossil) [MJ]	9,45E+01	1,15E+03	-2,57E+00	3,59E+01	6,13E+02	-8,43E+00
Acidification Potential (AP) [kg SO2 eq.]	4,08E-02	6,73E-02	-1,55E-04	5,07E-03	3,58E-02	-1,17E-03
Eutrophication Potential (EP) [kg Phosphate eq.]	2,87E-03	1,08E-02	-1,38E-05	6,30E-04	5,74E-03	-1,10E-04
Freshwater Aquatic Ecotoxicity Pot. (FAETP) [kg DCB eq.]	4,89E-02	4,34E-01	-1,12E-04	2,24E-02	2,31E-01	-1,30E-02
Global Warming Potential (GWP 100 years) [kg CO2 eq.]	7,17E+00	8,79E+01	2,45E-01	2,09E+00	4,68E+01	4,20E-02
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	2,12E+00	2,36E+00	-4,29E-03	8,23E-01	1,25E+00	-6,52E-01
Marine Aquatic Ecotoxicity Pot. (MAETP) [kg DCB eq.]	2,57E+03	1,20E+03	4,19E+00	1,90E+02	6,38E+02	-1,01E+02
Ozone Layer Depletion Potential (ODP,) [kg R11 eq.]	1,45E-09	5,24E-11	7,90E-10	1,00E-09	2,79E-11	2,10E-10
Photochemical. Ozone Creation Potent (POCP) [kg Ethene eq.]	2,35E-03	9,35E-03	-2,50E-05	5,16E-04	4,98E-03	-1,32E-04
Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	4,03E-02	3,49E-02	1,06E-05	1,39E-02	1,86E-02	-2,95E-03
Primary energy demand [MJ]	1,20E+02	1,30E+03	-3,50E+00	4,68E+01	6,93E+02	-1,29E+01
Total freshwater consumption (including rainwater) [kg]	7,65E+01	1,02E+03	-6,39E-01	2,47E+01	5,45E+02	-5,41E+00

ANNEX G - SENSITIVITY ANALYSIS

G.1. END OF LIFE

Synoptic charter

Figure G.1 - Synoptic framework sensitivity GWP indicator behavior.



Numbers

Table G.1 – GWP results according to the different EoL options and reference on weight impact decrease among standard and innovative solution.

Component					
Name	**Weight decrease**	**Benchmark**	**Scenario 1**	**Scenario 2**	**Scenario 3**
AIM	-14%	38,33	38,33	38,33	40,76
TB	-22%	-3,00	0,84	-7,84	-5,70
MU	-2%	15,53	15,82	15,03	15,41
FT	-33%	4,81	4,81	4,81	7,28
DSH	-16%	1,98	1,98	1,98	4,48 -
PBS	-7%	25,58	25,58	25,58	28,13
BP	-46%	8,58	8,91	8,26	8,72
CM2	-51%	44,63	18,90	19,06	21,37
SA1,3	-31%	4,71	5,63	3,85	0,81
SA2	-43%	6,86	7,36	6,50	3,99
RE	-34%	19,38	19,38	19,38	21,83

G.2 SECONDARY EFFECT (SE)

Table G.2 – Use phase impact comparison considering secondary effect (SE).

Impact category	Component		Use	Use FRV SE	Scenario SE
GWP	AIM	Standard	1.37E+01	2.48E+01	3.78E+01
		Innovative	1.17E+01	2.12E+01	2.60E+01
	TB	Standard	5.93E+00	1.15E+01	1.14E+01
		Innovative	4.63E+00	8.95E+00	1.07E+01
	MU	Standard	2.01E+01	4.63E+01	6.17E+01
		Innovative	1.97E+01	4.53E+01	5.98E+01
	FT	Standard	3.86E+01	7.75E+01	9.56E+01
		Innovative	2.60E+01	5.22E+01	7.19E+01
	DSB	Standard	1.90E+01	3.78E+01	5.32E+01
		Innovative	1.59E+01	3.16E+01	4.85E+01
	PBS	Standard	5.91E+00	1.19E+01	1.39E+01
		Innovative	5.51E+00	1.11E+01	1.21E+01
	BP	Standard	6.86E+00	1.85E+01	2.50E+01
		Innovative	3.70E+00	9.96E+00	1.56E+01
	CM	Standard	1.50E+02	2.74E+02	7.61E+02
		Innovative1,3	1.23E+02	2.26E+02	3.12E+02
		Innov.2	7.37E+01	1.35E+02	2.69E+02
	SA	Standard	1.51E+01	2.78E+01	3.69E+01
		Innovative1	1.04E+01	1.59E+01	2.65E+01
		Innovative2	8.69E+00	1.91E+01	2.81E+01
	RE	Standard	2.66E+00	5.47E+00	1.04E+01
		Innovative	1.75E+00	3.60E+00	6.94E+00

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