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ANALYSIS LCA OF THE RACE UP TEAM MG15

Student: Enric Carreras Olaizola

Professor: Anna Stoppato

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ABSTRACT

Environmental pollution and climate change are two issues of particular importance, towards which public opinion has been increasing attention in recent decades, also because the consequences of these phenomena, such as frequent storms, are clearly visible.

The main purpose of the research is to illustrate the method of assessing the environmental impact of a process with an analysis called Life Cycle Assessment (LCA).

In the first part of this report, the LCA analysis is presented in a general way, it description and methodological framework, with a brief description of all its phases and procedures.

In the second part, a LCA analysis will be done for the new internal combustion engine promoted by Race Up Team of University of Padova, MG15. Unfortunately, data collection has been a limitation when carrying out a detailed study, so that the results obtained are the beginning of an object of study in the future

In the third and final part, a report on the reordering of data relating to a Formula SAE vehicle of the Race-Up team of the University of Padua is reported, with the aim of comparing results obtained with the ones obtained in a previous car, developed in 2013.

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1. FOREWORD

1.1 Motivation

In order to finish my higher university studies with a specialization in the energy sector, I have chosen a topic of special interest and importance today.

Everyone knows terms like global warming or acid rain. The press talks about indices and indicators to evaluate the different types of impact. However, there is a specific methodology to assess the different types of impact, which are classified into different categories.

This analysis is called LCA, and consists of a specific methodology that is the result of development and evolution, as more effects derived from many of the anthropological activities, of the different activities that constitute a process, become known.

The choice of a topic so widespread but at the same time so unknown has been the main incentive to guide my thesis.

Secondly, I wanted to focus the object of study in a practical field, so that a theoretical framework can be developed and consequently an analysis of a specific topic can be prepared.

The analysis is carried out on the Formula student car proposed by the Race Up team of the University of Padova, in order to be compared a posteriori with the results of previous studies.

As an energy engineer, the effects produced by our industrial activities, and how these effects affect our lives, are of great interest.

1.2 Prerequisites

To develop a complex vehicle life cycle analysis and so the thesis, certain requirements will be necessary.

First of all, knowledge about the different processes and materials on which the vehicle is made. If a specific material is not found, adapt a coherent solution to modify and complete the study without drastic changes in the results.

Second, access to data, divided into two: on the one hand, access to databases and libraries that reflect the materials and processes used. On the other hand, specific information about the car, in which the construction processes of the car are reflected, as well as the materials used.

Finally, to facilitate the calculations, a software that includes databases and has the numerical resolution capacity to evaluate the different environmental impacts.

2. INTRODUCTION

1.1 Goal of the Thesis

Two main objectives will be pursued in this thesis:

On the one hand, to develop a theoretical framework on life cycle analysis, from standardized procedures to the specific software developed for it.

On the other hand, once the working methodology of the LCA analysis is understood, study the real case of the racing car proposed by the Race Up team.

From this second objective a third will be derived, which will be the comparison with a previous study, dated from 2013. The main objective will be, on the one hand, to see the differences and similarities between both models: in practically a decade, the standards regulations have changed and, therefore, we will surely have very different results that will be very difficult to compare.

Even so, it is intended to make a comparison, as far as possible, between both machines.

This work aims to give a first and generic idea of the different environmental impacts that each system of the car supposes. As explained in the following section, the study is not detailed, since data collection has been a clear limitation for the development of the work.

1.2 Scope of the Thesis

The scope of the practical framework of this thesis is the LCA analysis of the car proposed by Race Up.

For this analysis, the following scopes are defined:

1. The manufacture of the car is contemplated only in a framework of materials. Each system is made up of different subsystems which in turn are made up of components, which will be introduced exclusively as masses of a specific material. The chosen material is either the only material that the system is made of (for example, the frame is made exclusively of carbon fiber) or different materials. In this case, it has been decided to define each of the materials in equal parts (in percentage) (the cables used are made of 25% aluminium, copper, silver and plastic). All this set of assumptions is due to the impossibility of acquiring all the data, which is the most critical and difficult phase of the analysis.

2. The processes that have been carried out once raw materials have been purchased, as well as moulding, ironing, printing have not been taken into consideration.

3. As in the previous point, the processes by which manufacturers have shaped their products (for example, for a screw, from the processing of the wire rod to the threading of the screw) have not been taken into account. .

4. Thus, the objective of the analysis is to have a first approach on how each of the systems and subcomponents of the car affect the environment, and what is the relevance of each impact.

5. Following the previous study model (for the internal combustion car proposed by the same Race Up team in 2013), a comparative analysis between both models will be attempted, although due to the multiple changes in the databases (update of different damages and indicators) a reliable comparison is not guaranteed.

6. Finally, this study is more qualitative than quantitative, in the sense that it is intended to show how the consumption of raw materials affects the environment. The continuation of the study can be developed with an update of the necessary primary data and the set of required processes, in collaboration with the competition team.

3. LIFE CYCLE ASSESSMENT

3.1 Introduction

Life Cycle Assessment, defined as LCA, involves the evaluation of some aspects (commonly those environmental) of a product or a process during all stages of its life.

It is a method which allows us to analyse through an objective way the set of processes that make part of a certain chain of production of an object.

The aim of this analysis is the valuation of the energetic and environmental loads of an activity, and the set of resources required to make an object. Finally it is reported the environmental impact. This methodology is well defined in both ISO 14040 and ISO 14044

What is really important to clarify is that it is a process analysis. It is not an analysis of the final product: we do not analyse the object itself, which among other things can be produced with different methods, but we want to analyse how we arrived at the same. For this reason it is considered as a cradle-to-grave approach, precisely because it analyses the performance of the processes of the entire production chain, opposing even better: from cradle to cradle if we also consider the return of materials at the end of their life.

Life Cycle Assessment is composed by the next phases, which will be described in the following points:

- Goal and scope definition
- Inventory analysis
- Impact assessment
- Interpretation

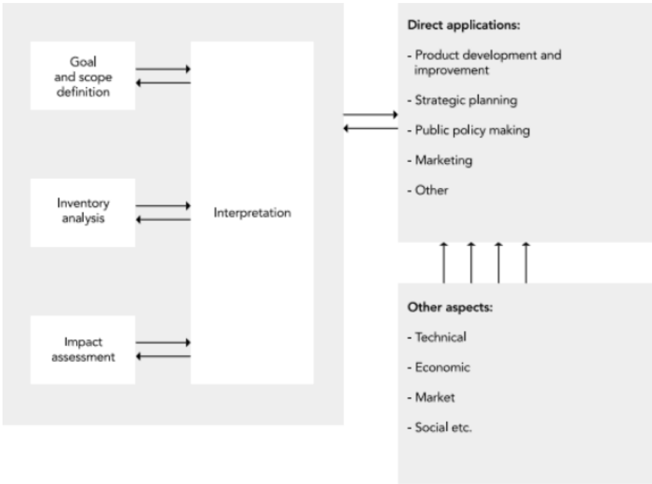


Figure 1: Life cycle assessment framework - phases of an LCA (ISO, 1997)

3.2 Phase 1: Goal and scope definition

In this critical phase, we find some needs that must be answered: purpose of the study, definition of functional unit, system boundaries applied and data quality. Goal and scope definition is the first step and contents the following issues:

3.2.1 Goal

The goal determines the accuracy level of the study and requirements. It includes the reasons for carrying out the study and to whom is done the study. Different examples of goals in LCA are the comparison between products which fulfils the same function, identification of the steps more critical in a process of manufacturing.

3.2.2 Scope

Sets the borders of the assessment, and which assessment methods will be used. It must be sufficiently defined to detail the starting goal. In this category, it is clearly identified: system to be studied, assumptions, limitations, data requirement, allocation procedures, methodology of impact assessment and the initial quality of the data.

3.2.3 Functional unit

It is essential to choose a correct functional unit because all data collected in the inventory (phase 2) will be related to it. The main function of the functional unit is to provide a normalized reference between input and output data and it must be clearly measurable. Basic examples as chosen functional units could be:

1. Per drink container you can use the litter, but you must also specify the quantity.
2. Transport systems passenger could be used, and the functional unit will be:
   [Kg gas/pers·km]

3.2.4 System boundaries

All inputs and outputs, processes and operations are defined in this category. For both input and output can be the overall result as well as of a single process. There are several criteria in LCA to decide the inputs. The most common criteria to choose inputs and outputs are mass and energy.

3.2.5 Data quality

The collection of the data is not done in this phase but in phase 2. However, we can distinguish between two kinds of data:

- Primary data: Those measured during the analysis directly with the proper instrument. Can be for input and output.

- Secondary data: those data are extracted by external data libraries due to the difficulty to measure, or the high cost it may involve (for example the emissions of a manufacturing processes requires sensors that in most cases are not available for small enterprises).

The aim of the data quality is to get the maximum primary data as possible, but it requires time and resources. Secondary data is useful in a geographical point of view.

3.3 Phase 2: Inventory analysis (LCI)

This phase is convolving the data collection and the empirical calculation procedures. It is the most demand part of the LCA analysis. The qualitative and quantitative data shall be collected for each unit process. It consists in the main issues:

3.3.1 Data collection

The most work intensive part of a life cycle assessment. The data collected constitute the input of the LCA. Depending on time and budget, several strategies are developed to collect these data. We can define two types of data:

- Foreground data: specific data to model the system. It describes the particular product or system of the study.

- Background data: It is usually found in databases and literature. Data for generic energy, transport, materials systems.

The result of data collection can be presented in an inventory table such as the following:

	TYPE	UNIT	AMOUNT
FUELS			
FEEDSTOCK			
RAW MATERIALS			
EMISSIONS			

Figure 2: Characteristic inventory table

3.4 Phase 3: Impact assessment (LCIA)

This phase consists in the analysis of the data collected in the previous stage, with the purpose of understanding the environmental effects caused by the productive activity developed by our system.

Those effects are generated due to the resources consumption and the release into the ambient. In this phase there are some compulsory stages and optional.

3.4.1 Mandatory phases

3.4.1.1 Category definition

The impact categories are selected in order to describe the products or product systems impacts. There are several categories: abiotic and biotic resources, global warming, land use, stratospheric ozone depletion, human toxicological impacts, work environment, eutrophication and acidification.

3.4.1.2 Classification

It consists in the classification of those macro-categories we in the category definition. For example, some emissions can belong to different categories: CO_2 emissions may can cause greenhouse effect and human toxicological impact.

In some cases it is easy to estimate the relationship impact/effect, as it is the case of greenhouse effect, in which is it founded the kg of carbon dioxide produced. In other cases, for example the effect of a swirl, the effect to the people is directly related to the distance.

3.4.1.3 Characterization

Of those sub-categories defined in the classification, it is needed to associate a certain numerical quantity expressed to the reference characteristic unit.

It is a quantitative step in which it is assigned the relative contribution of each input and output to the different categories defined previously. This percentage of contribution of inputs and outputs is estimated, and normally is a step done directly by software used.

3.4.2 Non mandatory phases

LCA procedure ends with characterization. However, there are two further steps in which the results are better interpreted according to normalized values and weights assigned to assessment categories.

3.4.2.1 Normalization

Compare the values obtained with standard values in order to normalize them and objectively compare all the possible LCAs.

3.4.2.2 Weighing

Useful for comparing different processes. The objective is to try to draw the overall conclusions of the analysis, which will be characterized by a unique value. To obtain it, weights will be assigned to each indicator and will be summed to obtain the maxim value.

To give a relative importance to the different results, it is necessary to weigh. This step is not scientific based. It is obtained by statistical data obtained in similar studies done before.

3.5 Phase 4: Interpretation

Interpretation is the fourth phase in life cycle assessment. It contains the following issues according to ISO14044:

- Identification of significant environmental issues.
- Evaluation.
- Conclusions and recommendations.

Phase of interpretation is essential to validate the study and give veracity on the previous technical phases; it consists in a systematic procedure to identify, quantify and evaluate the conclusions of the inventory analysis.

3.5.1 Identification of significant environmental issues

The objective is to collect all the information of the LCIA phase and structure it in such a way that it is possible to determine the set of problems defined in the initial goal description.

It presents the following structure for relevant information:

- Results from other different phases must be present in form of summarizing tables and figures.

- Valuation methods used

- Methodological choices.

3.5.2 Evaluation

The aim of this step is to give validity to the scope of the study: it must present, firstly, the results obtained in a qualitative or quantitative way in a form that the receivers are clearly understanding the outcome.

Secondly, and if needed, study possible alternatives to achieve better result. Finally, if during the study it appeared any change with the initial data used must be specified.

To reinforce the calculations done, there are three elements that can be used: completeness, sensitivity and consistency check. However, in this study those points will not be mentioned into further detail.

3.5.3 Conclusions and recommendations

It is basically the same as the conclusions in a scientific report: if the goals and scope of the study have been achieved, and possible alternatives to reach a better performance.

4. FEATURED TOOLS

4.1 Softwares

The consuming time surrounding LCA analysis has prompted the development of different software programs. The specific software allows us to assemble the LCI data and make the LCIA calculations. They provide libraries of databases for generic LCA processes. Introducing the correct inputs, those different software allows us to obtain the different impact categories according to different methods, which will be described later on.

LCA software with the highest market shares are SimaPro and GaBi. Both have a similar stucture with different style (or interface).

4.1.1 SimaPro

This software complies with ISO 14040/14044 and provides both phase 2 and 3 (LCI and LCIA). The product is a collection of processes, assembles and wastes. In this software, several libraries are added with information of different substances, materials, wastes and processes.

SimaPro

Figure 3: Logo software SimaPro

Also in this software there are included different methodologies for impact assessment, which will allow to evaluate the different impact categories. The easy interface and the visibility and the way for delivered data make this software one optimal solution for LCA analysis.

SimaPro can deal with many unit processes in one calculation. The algorithm uses a product system in a matrix inversion.

4.1.2 GaBi

GaBi is also fully compliant with ISO 14040/14044 and provides both phase 1 and 2 (LCI and LCIA). The product is a collection of plans, which contain assembles. The general structure is similar to SimaPro, however it is not divided in processes but in plans.

GaBi
Product Sustainability
Performance

Figure 4: Logo software GaBi

One of the biggest deals with GaBi is that it works with different databases, but in order to work properly, databases required for the project must be merged to be used. The structure has a higher complexity compared to SimaPro.

The algorithm used by GaBi is sequential, which goes from one plan to other, in order to scale the inputs fixed.

4.2 Methodologies for impact assessment

4.2.1 IPCC 2021

This method developed by the Intergovernmental Panel on Climate Change is evaluating the impact category Climate Change, sometimes called Global Warming.

IPCC has three different versions of the method, depending on the timeframes, in terms of cumulative radioactive forcing greenhouse gases (GHG) after 20,100 or even 500 years.

At midpoint level, which will be our focus of study, it distinguish three different GWP indicators:

- GWP biogenic: derives directly from biomass combustion process.
- GWP fossil: derives directly from fossil fuels.

- GWP land transformation: derives from the occupation of the land, in the sense that the origin has been changed and, therefore, it can be defined as an emission.

Evidently the GWP due to fossil fuels will be the majority component, although, as we will see in the experimental framework, all three are normalized.

4.2.2 ReCiPe 2016 Midpoint (H)

ReciPe is a method for LCIA that was developed in 2008 by RIVM, Radboud University Nijmegen, Leiden University and PRé Sustainability.

The main objective is to transform the large amount of results into a fixed number of indicators. Those indicators represent the environmental impact category damage.

By applying the Recipe 2016 Midpoint (H) methodology, thus quantifying the emissions and resource extractions of the systems in a limited number of environmental impact categories. The environmental impact categories evaluated by the Recipe 2016 Midpoint (H) method are shown in ***Figure 5.***

Environmental impact categories	Units
Global warming	kg CO2 eq
Stratospheric ozone depletion	kg CFC11 eq
Ionizing radiation	kBq Co-60 eq
Ozone formation, Human health	kg NOx eq
Fine particulate matter formation	kg PM2.5 eq
Ozone formation, Terrestrial ecosystems	kg NOx eq
Terrestrial acidification	kg SO2 eq
Freshwater eutrophication	kg P eq
Marine eutrophication	kg N eq
Terrestrial ecotoxicity	kg 1,4-DCB
Freshwater ecotoxicity	kg 1,4-DCB
Marine ecotoxicity	kg 1,4-DCB
Human carcinogenic toxicity	kg 1,4-DCB
Human non-carcinogenic toxicity	kg 1,4-DCB
Land use	m2a crop eq
Mineral resource scarcity	kg Cu eq
Fossil resource scarcity	kg oil eq
Water consumption	m3

Figure 5: summarizing table impact categories included in ReCiPe 2016

Of the aforementioned environmental impact categories, this project will initially focus on the evaluation of those listed below. However, once the results are obtained, those environmental impact categories that show a greater difference for both treatment alternatives will also be analysed.

The benefit of studying the midpoint method for the different categories is that results are scientifically robust, meanwhile in the end point, the results are a estimation of the Area of Protection level.

By using the correct method for the studies of different categories we will reach more transcendental results, as proposes *ILD Handbook* [1]

1. Global warming (Greenhouse Gas emissions, kg CO2 equivalent).

The progressive increase in the planet's temperature due to greenhouse gases translates into an interest in knowing, both on the part of customers and producers, the so-called carbon footprint.

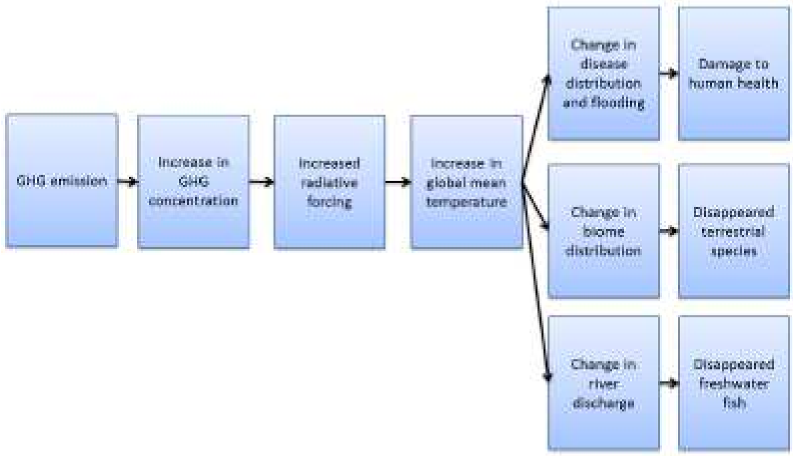


Figure 6: Cause and effect chain from GHG emission to impact categories

2. Terrestrial ecotoxicological (kg 1,4-Dichlorobenzene equivalent).

It predicts the effects of pollution in those ecosystems in which environmental quality is being lost due to pollution and human activities. For example, the pollution produced by wastewater discharges and leachate from uncontrolled landfills, among others, produce accumulation of polluting substances in the soil.

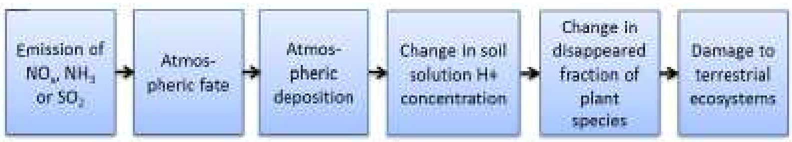


Figure 7: Cause-and-effect chain for emissions of ozone depleting substances to human health

[1] ILCD Handbook, Recommendations for Life Cycle Impact Assessment in the European context.

3. Carcinogenic human toxicity (kg 1,4-Dichlorobenzene equivalent).

The release of gases, substances or particles into the atmosphere can cause direct damage to the atmosphere, altering its composition and functionality. This can cause damage to the ozone layer by increasing ultraviolet radiation on the earth's surface, increasing the risks to human health, in which cancer can be developed.

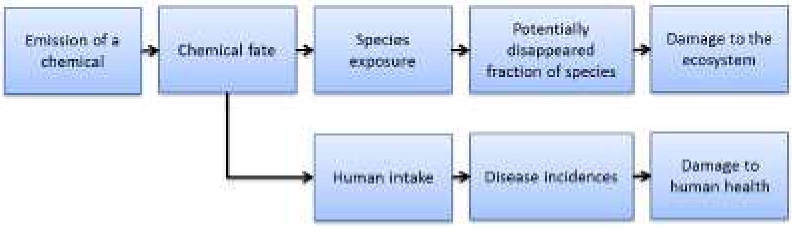


Figure 8: Cause-and-effect chain, from emissions to damage to the ecosystem and damage to human health

4. Scarcity of fossil resources (kg oil eq)

The current consumption of fossil fuels has increased, and this is causing changes in greenhouse gases, since burning fossil fuels increases the emission of carbon dioxide, causing an increase in temperature and global warming. Fossil resources are limited as they take a long time to generate, so they are likely to run out if no action is taken.

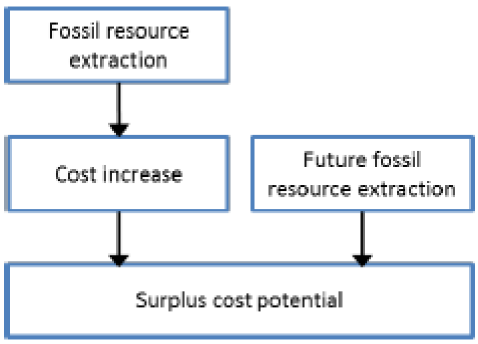


Figure 9: Cause-and-effect chain, from fossil resource extraction to natural resource scarcity

5. Freshwater eutrophication

Occurs when there is a discharge of into freshwater bodies and consequently there is a rising in nutrient levels. The ecological impact is clearly visible: increasing of autotrophic organism as algae, and heterotrophic species such as invertebrates and fish.

At the same time, this factor leads to loss of species, due to natural adaptation to environment.

Figure 10: Cause-and-effect chain for Phosphorus emissions causing

6. Marine ecotoxicity

Based on the potential impact in which metals (mostly cobalt, copper, manganese and zinc) are expulsed to oceans and leads to toxic effects.
The following scheme shows the link between the environmental impact categories and the three areas of protection:

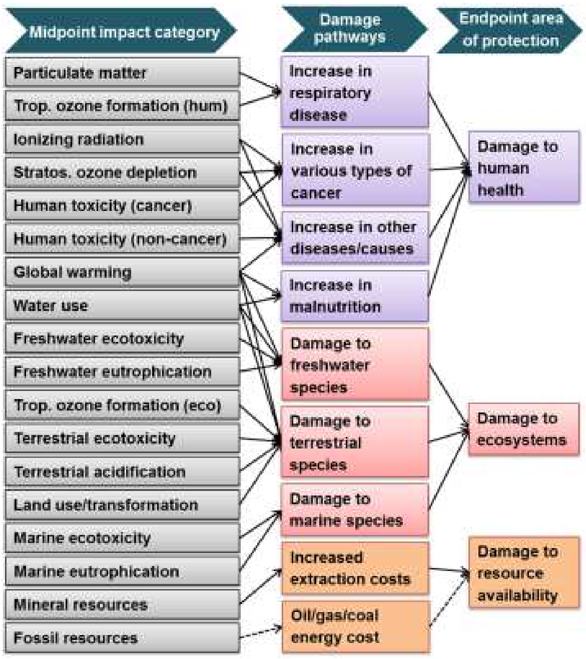


Figure 11: ReCiPe summarizing Midpoint to Endpoint impact categories

This scheme shows the phases of category definition and classification. The scope of our study will end in the midpoint valuation, which will be compared with previous models.

5. RACE UP MG15

The Race Up MG15, is the car designed by the Race Up Team car, by students and members from the University of Padova. It is an internal combustion engine, and it is composed by the following sub-systems:

- Frame & Body
- Engine & Drivetrain
- Brake system
- Steering System
- Suspension
- Electrical system
- Wheels & Tires
- Other components

Figure 12: MG15 Race Up car

5.1 Frame and Body

The system frame and body constitutes the main supporting structure in which the rest of the components are attached. It must support the vehicle mechanical components and be robust against the dynamic forces where it is involved. It is composed by a total of 23 subsystems, which are well defined in Annex I.

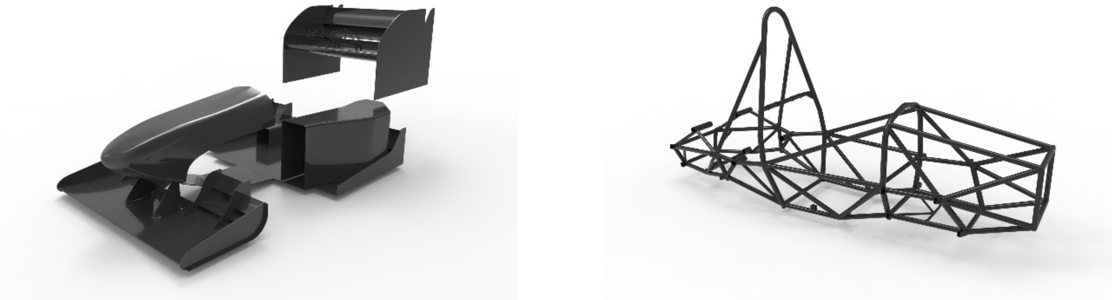


Figure 13: Frame and car body

5.2 Engine and Drivetrain

The drive train consists in the group of components that delivers power from the engine to the wheels. The powertrain is including both engine and drive train.

In RaceUp MG15 it consists in a total of 38 subsystems in which are included the engine block, gear-wheel, airbox and chain drive.

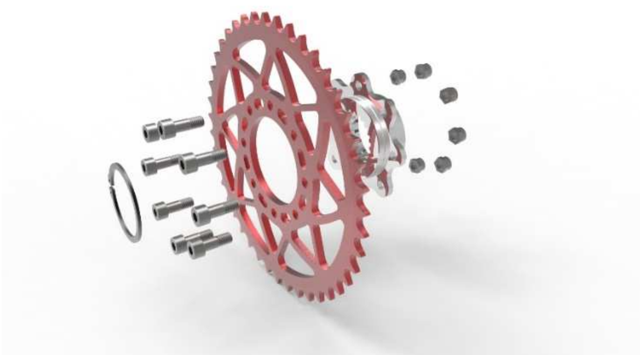


Figure 14: Gear-wheel assembly

5.3 Brake System

Brake system uses friction to slow the motion of the vehicle. The working principle is easy: it uses the kinetic energy from the wheels and converts it to thermal energy dissipated through brake pads.

Brake system in our prototype consists in 4 subsystems which are the brake line, pedals and stretcher support.

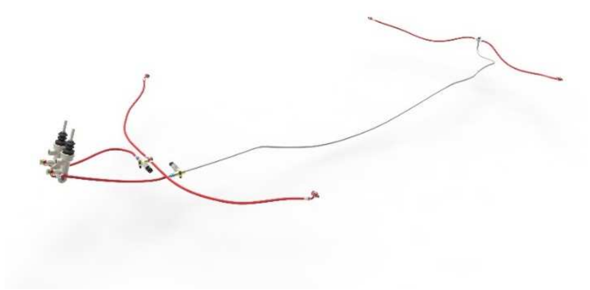


Figure 15: Brake lines view

5.4 Steering system

Steering system allows the movement of the car from the steering wheel through the swivelling movement of the wheels. Basically it allows the driver to guide the vehicle.

Our system is divided in 8 subsystems in which are included racks, gimbals and steering column.

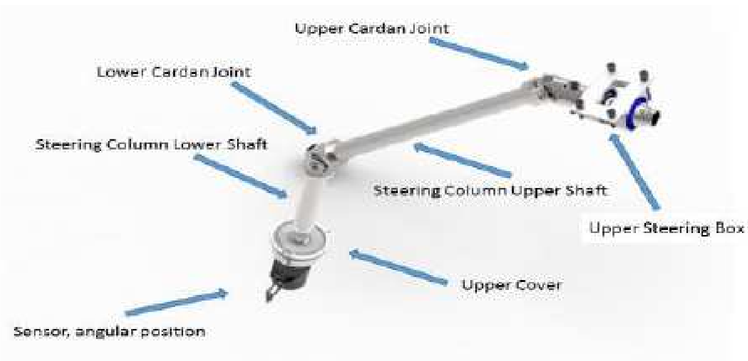


Figure 16: Steering system assembl

5.5 Suspension

The suspension system is the nexus between the wheels and the vehicle. It allows the relative motion between wheels and system, and the principal task is holding the car against vibrations, which become uncomfortable for the user. In our project it is subdivided in 22 subsystems.

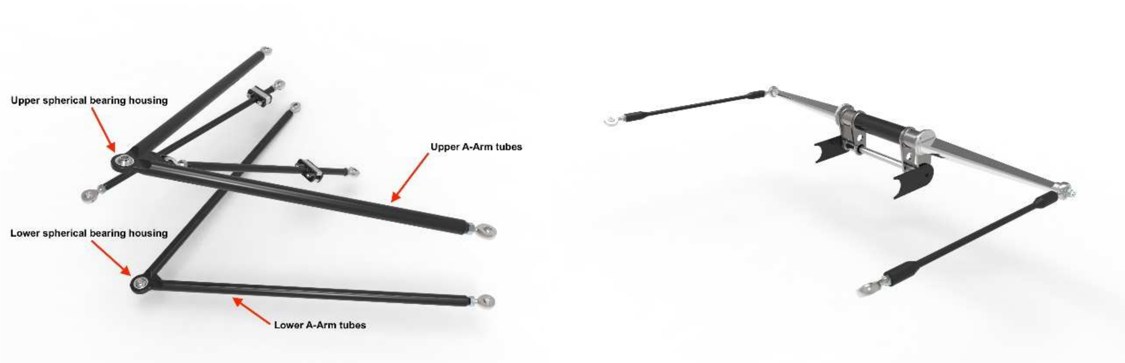


Figure 17: Back triangle (L) and Back ARB (R)

5.6 Electrical System

In the category of electrical system it has been included all devices related to electrical components, such as the display in the main panel, WIFI device, all controlling sensors, wirings, voltage regulator and other components. It is subdivided in 8 subsystems.

5.7 Wheels and tyres

Allow the real movement of the vehicle through the friction between the floor and the wheel. Due to the lack of information, it has been created as a single process composed by magnesium and rubber in the same proportion as the real system.

Figure 18: Pneumatics and tires

5.8 Other components

In this category are included those components missing, and some approximations, such as bolts, screws and nuts that are not considered specifically in the other systems. It is also included the black painting and sponsor labels.

6. LCA MG15 ANALYSIS

6.1 Goal and scope definition

The objective of this thesis is to carry out an LCA study to determine the systems that cause the greatest environmental impact of the MG15 racing car.

As far as possible, the second objective is to compare it with a car, also with internal combustion, proposed by the same team almost a decade ago, the MG13.

The definition of the scope of work is directly and closely related to the availability of data.

On the one hand, the type of study is defined as cradle-to-gate, in which the evaluation of the environmental impact begins with the extraction of the raw materials necessary for its production until its manufacture. The reason for this choice is simple: the useful life of this machine is usually short, around 150 km. For this reason, the majority impact at the environmental level is due more to the manufacturing process than to the use itself.

On the other hand, the level of detail of the study depends on the cut-off criteria. The total inventory is unknown for any type of environmental impact analysis study. In this case, we must ask ourselves the following question: are the resources necessary to acquire this information relevant to the study?

For our study in particular, the established criteria have been defined by the quality of the data:

1. The production processes necessary to manufacture a purchased component are not considered. In other words, the components that have been purchased are counted as mass blocks of a certain material, so the analysis only contemplates their extraction.

2. The subsystems made up of more than one material have been introduced as masses with the same percentage for each material: for the wiring system, 25% copper, plastic, aluminium and silver have been taken in equal parts.

3. The internal processes carried out by the team are practically impossible to quantify: the energy needed to print a particular part using 3D printing supposes a level of detail that is not contemplated.

In short, all the inputs of the system are accounted for as tares of the materials that make up each subsystem.

With all this brief definition, the functional unit of the system is the car itself: as previously mentioned, the useful life of the vehicle is irrelevant for the study, since it will be short, so that the greatest impact will be in the production process, not in its utility.

This document gives rise to a continuity study, in which an exhaustive data collection will be able to detail the true environmental impact. However, as a result of this work, an environmental department could also be derived within the Race Up team, to evaluate possible materials that are compatible with competition regulations and functional at a structural level that reduce the environmental impact.

6.2 LCI

This stage is the most critical and laborious, since the collection of information is a complicated task. In this study, as mentioned above, the **analysis is of the Cradle to Gate** type (it is the analysis that takes into consideration only the production of the vehicle, from the extraction of the raw material to the arrival of the finished product at the factory gates, therefore before the finished product is transported to the consumer. Consequently, the phases of use and disposal are not considered), and the results are merely objective in order to have a small approximation of a possible future, extensive and detailed study if all data is collected.

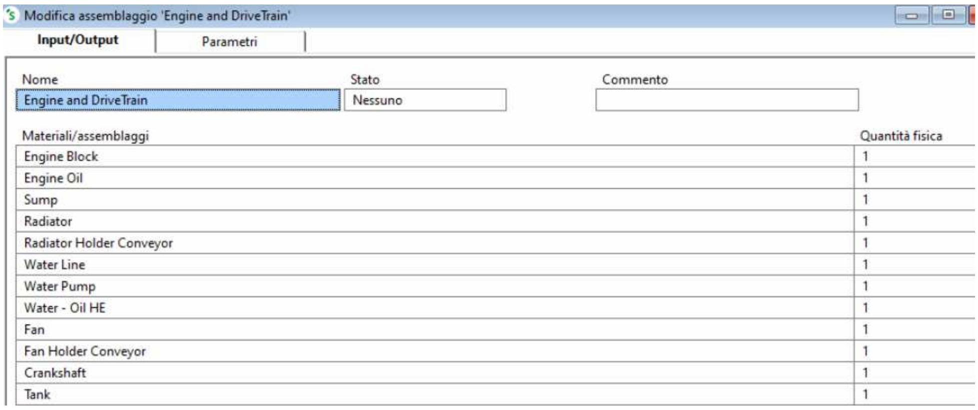
Regarding to the different data:

1. Foreground data refers to specific data needed to model the system. Data used was provided by RaceUp Team as a summarizing table divided in systems and subsystems, in which the components are described as macro-components done by different materials *(see in Annex I).*

2. Background data is data concerning generic materials, energy, transport and waste management systems. This is data that can be typical found in databases. Data Base used in this project is EcoInvent.

Foreground data has been introduced in SimaPro as an organized scheme: the different systems are processes and each process is defined as the mesh of different inputs (which mostly are materials taken from tecnosphere). The following image shows the interface on SimaPro

Figure 19: Main menu SimaPro interface



Materiali/assemblaggi	Quantità fisica
Engine Block	1
Engine Oil	1
Sump	1
Radiator	1
Radiator Holder Conveyor	1
Water Line	1
Water Pump	1
Water - Oil HE	1
Fan	1
Fan Holder Conveyor	1
Crankshaft	1
Tank	1

Figure 20: Engine and Drivetrain system project's interface

PROCESS CONSIDERATIONS

Some approaches and considerations have been done during the material's choosing process. All of them are considering in the following:

- Varnish: Acrylic varnish, without water, 87, 45% solution state.
- Stainless Steel: Steel, chromium steel 18/8.
- Aluminium foil: usually contains from 92-98% of alloy aluminium.

6.3 LCIA

When inventory analysis phase (LCI) is finished and fully detailed, the impact assessment starts. In this phase it is understood and evaluate the potential environment impact that our system produces.

It will be divided following the standards in ISO14040 in two parts:

- Mandatory phase: which will include category definition, classification and characterisation.

- Non-mandatory phase: To achieve a better understanding of impact categories, a normalization procedure will be considered.

6.3.1 Category definition and classification

It is a qualitative step whereby inputs and outputs are assigned to different impact categories based on the type of expected impact on the environment. The allocation must be based on scientific analysis of environmental processes relevant. The main purpose of this activity is to describe the potential environmental effects of inputs and outputs, and decide which environmental impacts are considered in the assessment. There are three broad categories of impacts as an end point (E):

- Natural resources
- Human health
- Ecological health

However, in this paper we intend to study the impact categories at the medium level (M), as defined in the theoretical framework.

In order to evaluate the category of Global Warming, the IPCC method will be used, meanwhile for the other categories mentioned in the point 4.2.1 will be used ReCiPe 2016.

6.3.2 Characterization

It is a quantitative step in which the relative contribution of each input and output in its assigned impact category; and the contributions are percentualized within each category.

The characterization must also be based on the scientific analysis of the processes relevant environmental.

We will see the characterization system by system of the Race Up car:

6.3.2.1 Frame and Body

IPCC 2021

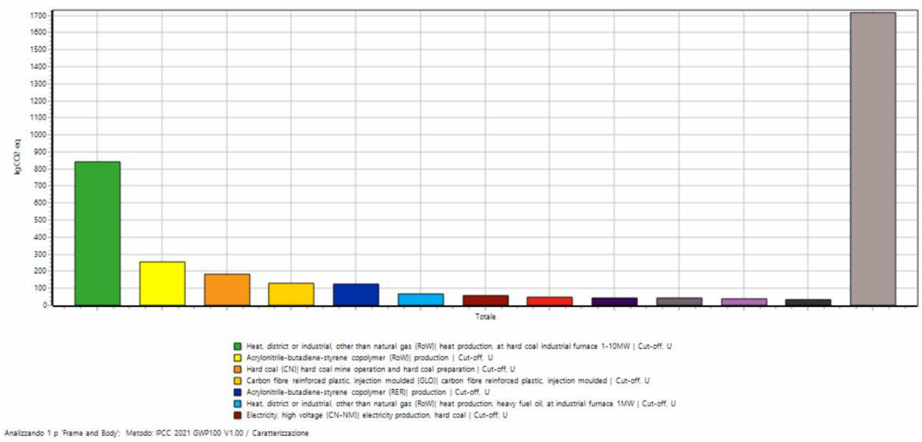


Figure 21: IPCC characterization Frame and Body contributing process

This first graphic shows the global warming impact measured in equivalent CO_2 kilograms, in terms of the contributing processes. The process with a highest impact is heat production at hard coal industrial furnace. The result is lightly above 1700 kg CO_2 eq.

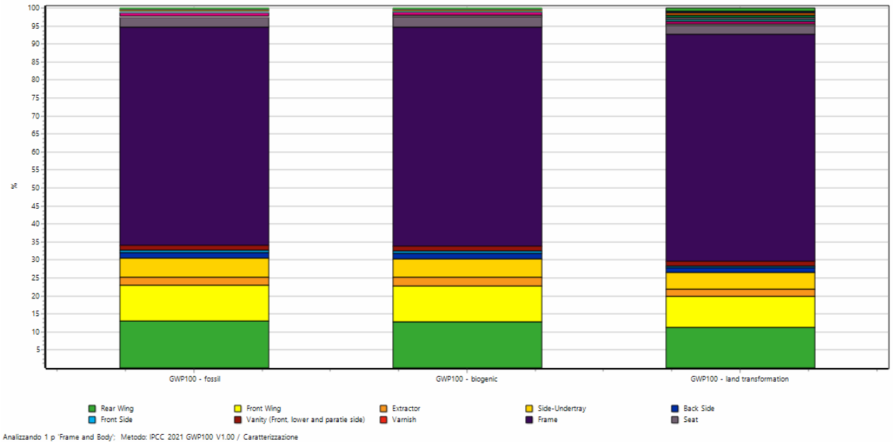


Figure 22: IPCC characterization GWP Frame and Body

This second graphic shows the characterization of global warming potential in terms of fossil, biogenic and land transformation resources, with high impact in the frame.

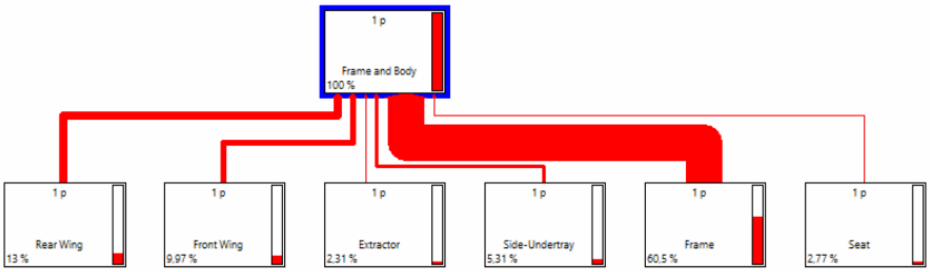


Figure 23: Process contribution grid Frame and Body

Finally, this third graphic shows the percentage contribution of subsystems by a grid diagram in the frame and body, cut in a 2% of significance. The most contributing process is the frame production.

ReCiPe 2016

With the solving method ReCiPe it can also be seen the global warming impact measured in equivalent CO_2 kilograms, in terms of the contributing processes. The result is lightly above 1700 kg CO_2 eq, which is practically then same as the one obtained by IPCC method:

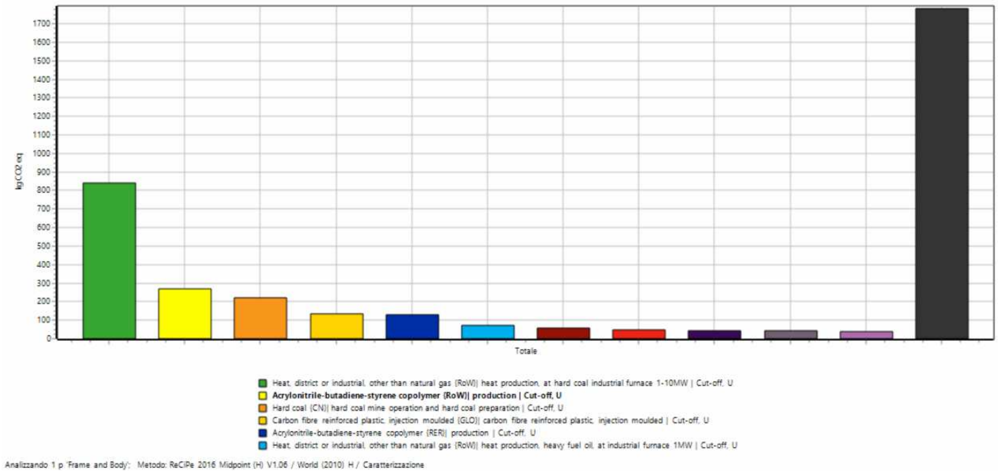


Figure 24: ReCiPe characterization Frame and Body contributing process

At this point it is interesting to see the midpoint categories affected by each subsystem, in a percentage way:

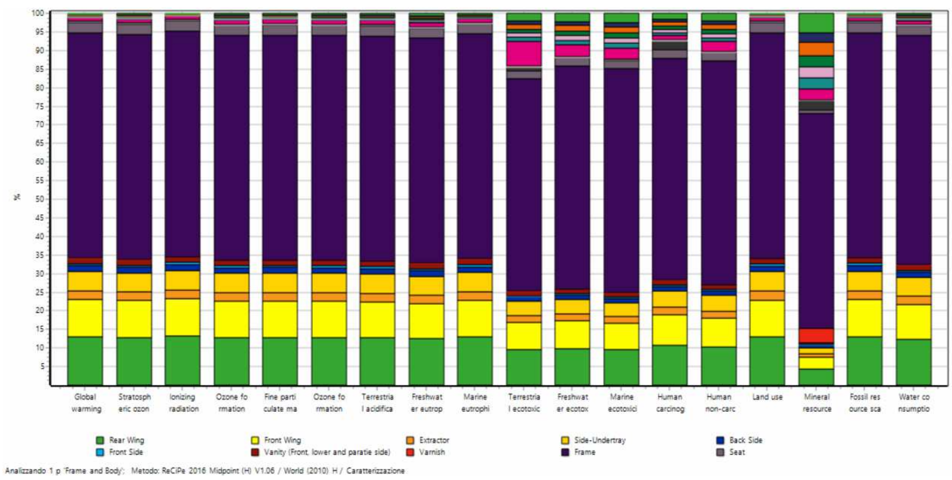


Figure 25: ReCiPe characterization Midpoint impact categories Frame and Body

With a cut in 1% of the contribution, it can be seen that the varnish has a lightly higher contribution in terrestrial ecotoxicity, and rear and front wings are less significant in mineral resource. However, the contribution of each subsystem in each impact category remains constant.

6.3.2.2 Engine and Drivetrain

IPCC 2021

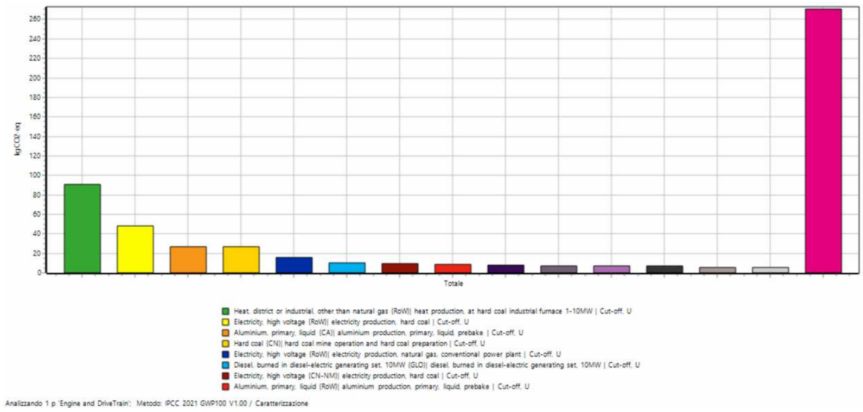


Figure 26: IPCC characterization Engine and Drivetrain contributing process

As in the previous case, the process with a highest impact is heat production at hard coal industrial furnace. The result is lightly above 260 kg CO_2 eq.

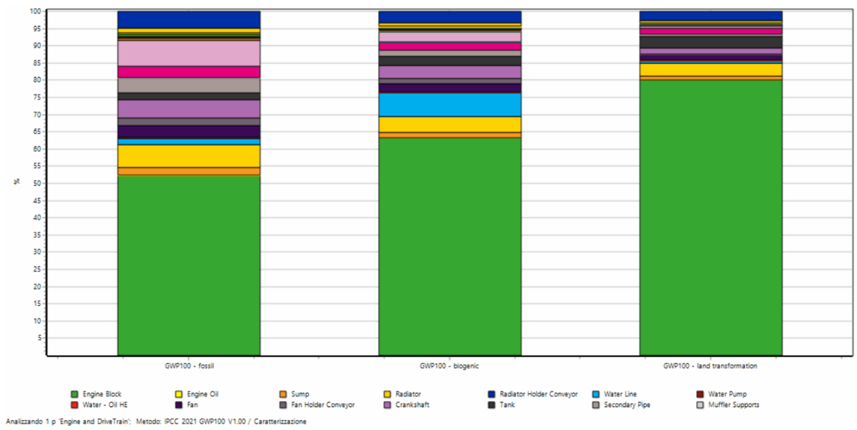


Figure 27: IPCC characterization GWP Engine and Drivetrain

As the graphic shows, the highest global warming impact in this graphic is due to the engine block.

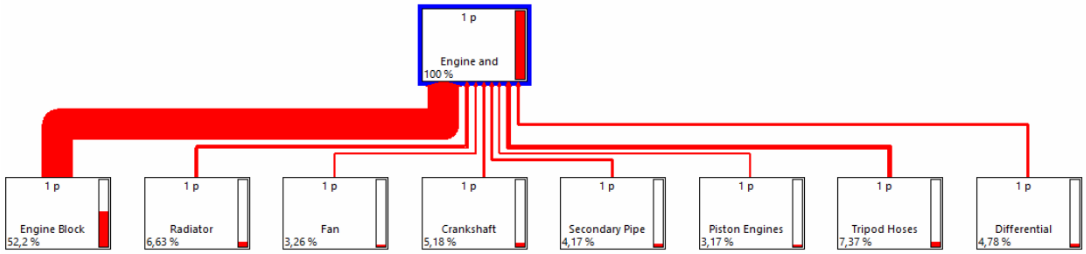


Figure 28: Process contribution grid Engine and Drivetrain

Finally, this third graphic shows the percentage contribution of subsystems by a grid diagram in the engine and drivetrain, cut in a 2% of significance. The most contributing process is the engine block production.

ReCiPe 2016

The global warming impact is also approximately 280 kg CO_2 eq:

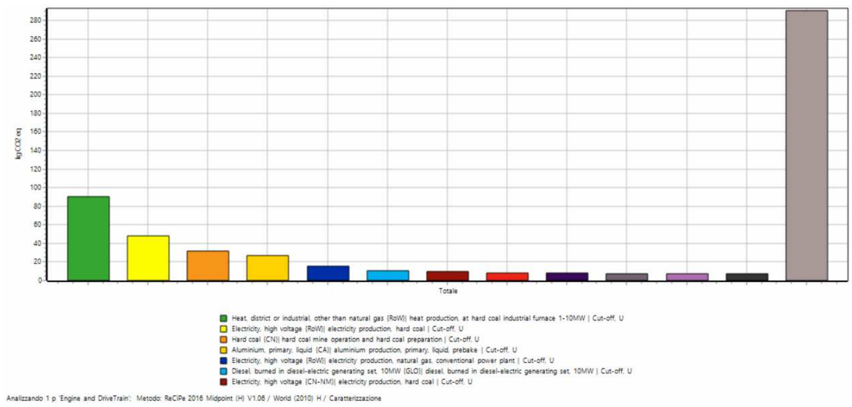


Figure 29: ReCiPe characterization Engine and Drivetrain contributing process

The characterization of category impacts is:

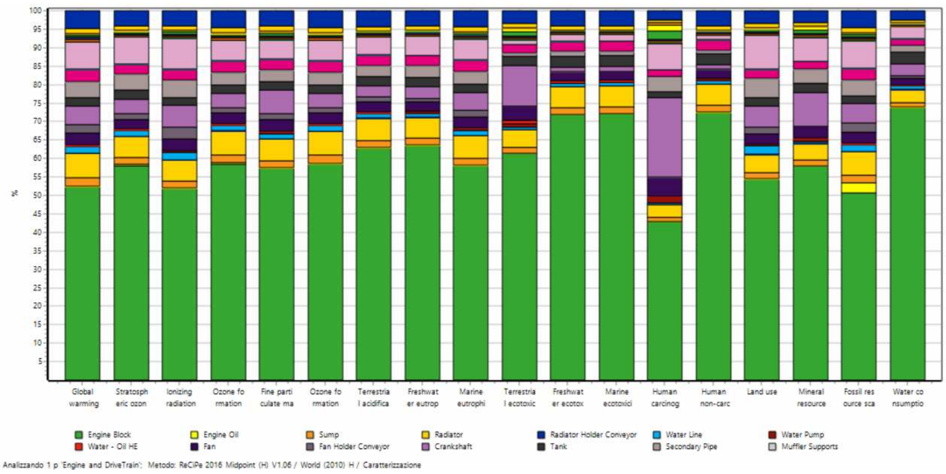


Figure 30: ReCiPe characterization Midpoint impact categories Engine and Drivetrain

Regarding to this graphic, special attention to the contribution of the crankshaft in the human carcinogen category.

6.3.2.3 Brake System

IPCC 2021

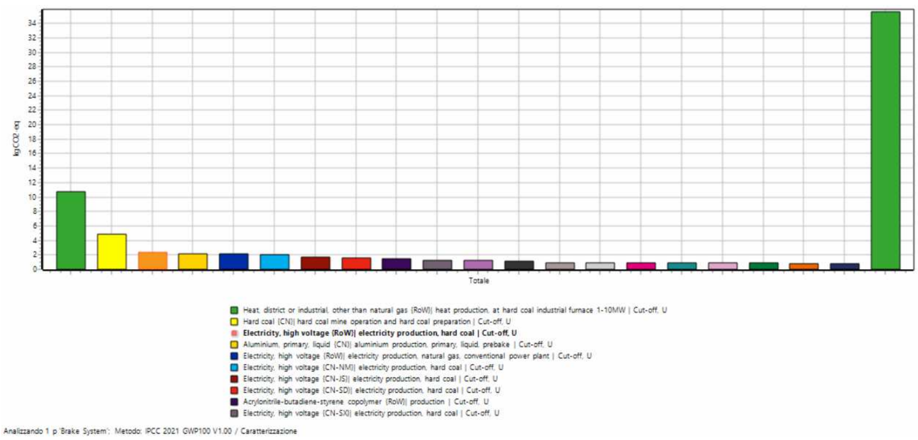


Figure 31: IPCC characterization Brake System contributing process

As in both previous cases, the process with a highest impact is heat production at hard coal industrial furnace. The result is lightly above 34 kg CO_2 eq. which is not really relevant compared to the other systems.

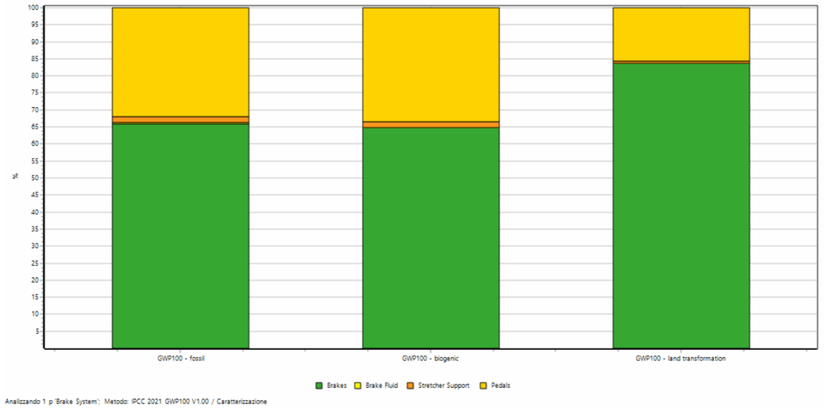


Figure 32: IPCC characterization GWP Brake System

The highest GWP impact is due to the brakes, and so it is the highest energy contribution in the following grid diagram:

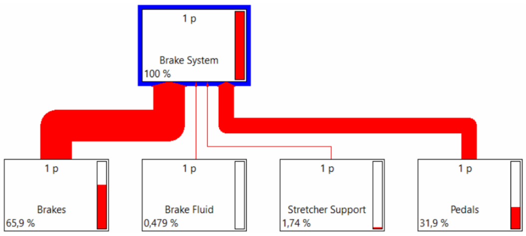


Figure 33: Process contribution grid Brake System

ReCiPe 2016

The results obtained for the contribution process are almost equal than the ones found with IPCC method.

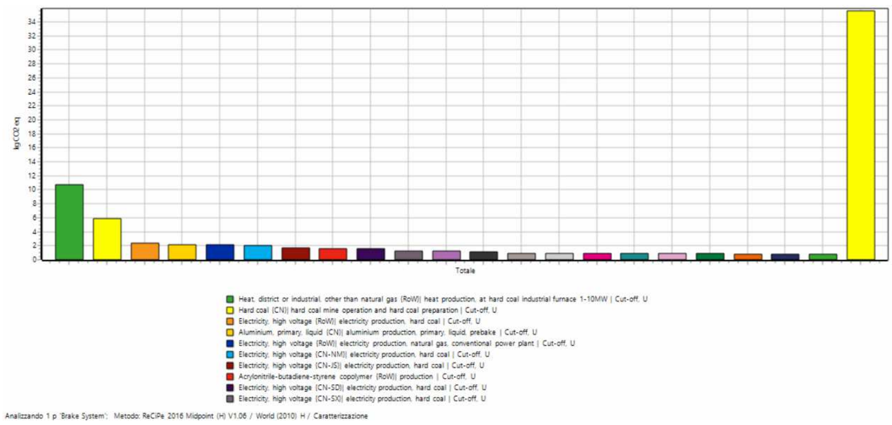


Figure 34: ReCiPe characterization Brake System contributing process

Regarding to the characterization, the most impacting subsystem in all categories are the brakes, and the stretcher support has a quite high impact in human carcinogen.

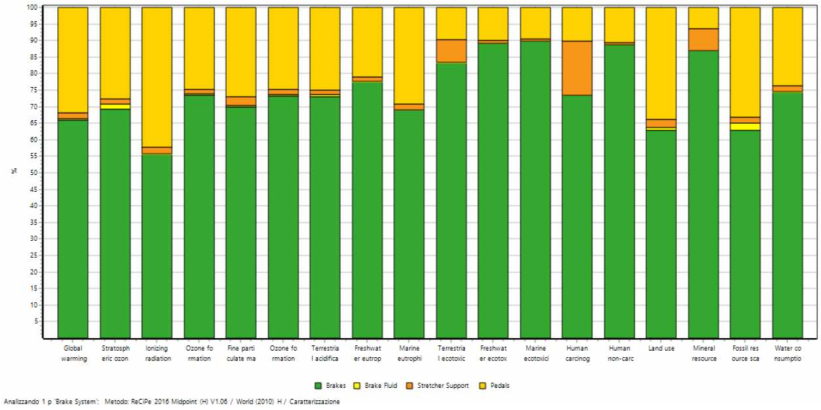


Figure 35: ReCiPe characterization Midpoint impact categories Brake System

6.3.2.4 Steering System

IPCC 2021

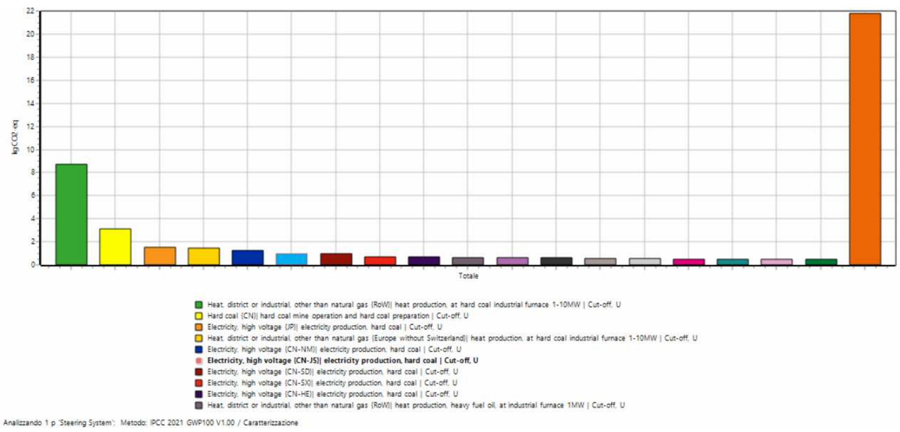


Figure 36: IPCC characterization Steering System contributing process

IPCC method shows that the highest contribution process is the production of heat, with a total amount of 22 kg CO_2.

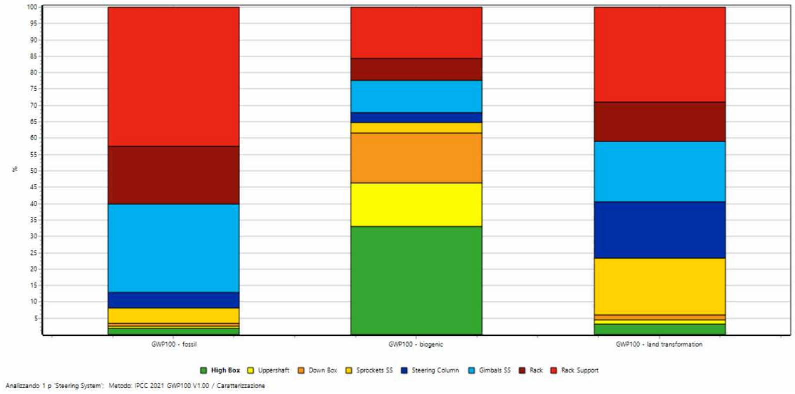


Figure 37: IPCC characterization GWP Steering System

Regarding to this graphic, we can observe a behaviour totally different from the previous ones: the indicated of global warming differs a lot according to the categories. Steering system is manly composed by aluminium (66%) and titanium (33%). In relation to the origin for obtaining titanium, many more fossil fuels are used than those derived from biomass.

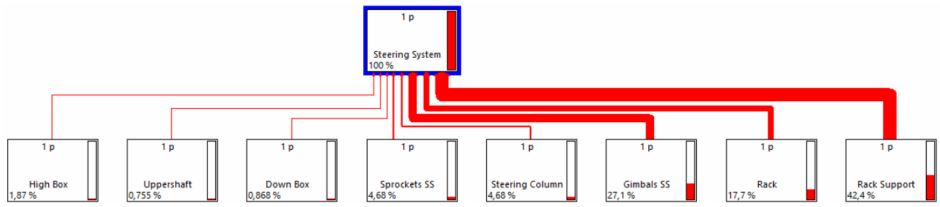


Figure 38: Process contribution grid Steering System

The components with the highest energy consumption are the rack support, gimbals and properly the rack, in this order.

ReCiPe 2016

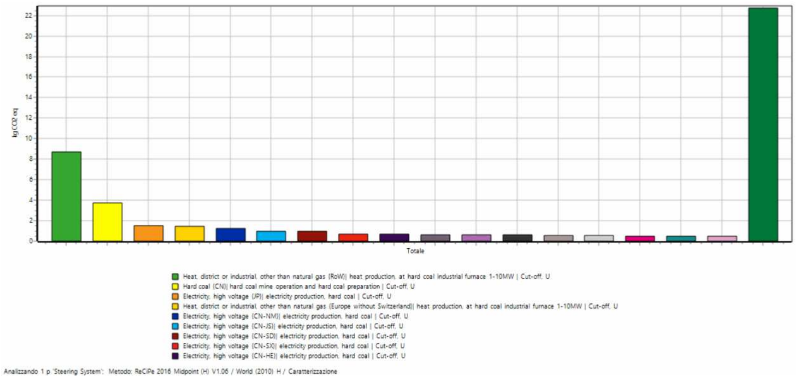


Figure 39: ReCiPe characterization Steering System contributing process

Following the same trend as with the IPCC method, total global warming is slightly above 22 kg CO2.

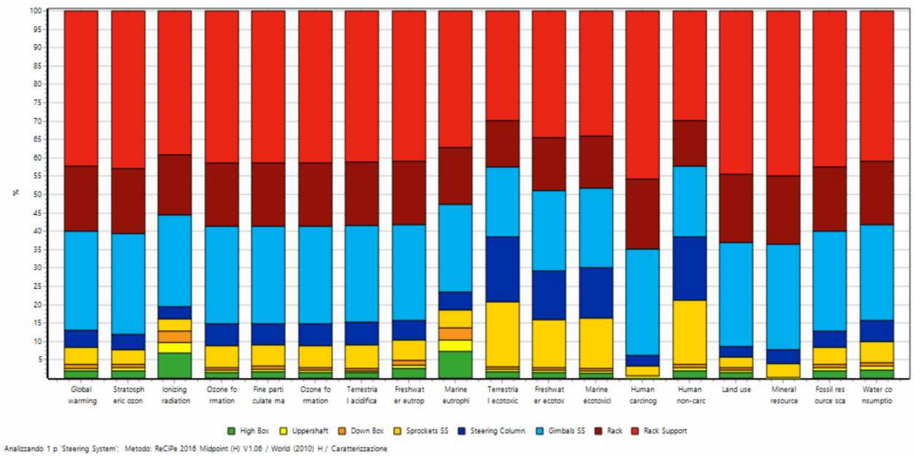


Figure 40: ReCiPe characterization Midpoint impact categories Steering System

Rack support has the highest impact in all categories, followed by gimbals. Sprockets have a high impact contribution in terrestrial ecotoxicity, however it is contained in human carcinogen.

6.3.2.5 Suspension System

IPCC 2021

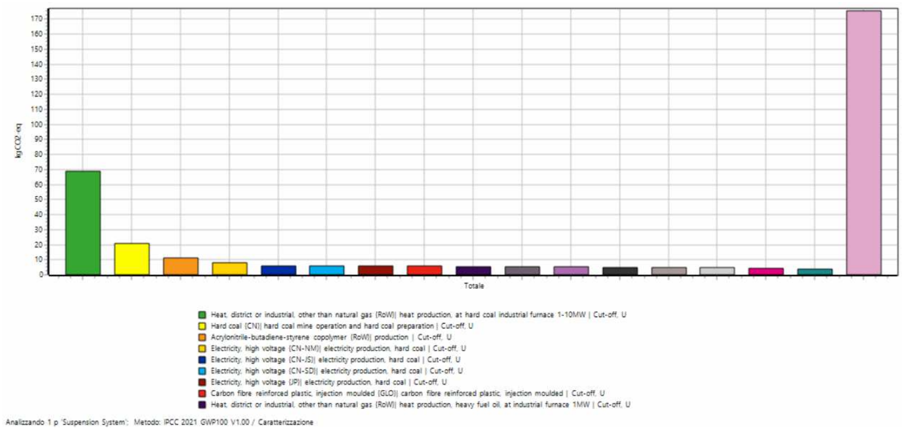


Figure 41: IPCC characterization Suspension System contributing process

The result is lightly above 170 kg CO2 eq. which is quite relevant compared to the other systems, and the major precedence comes from hard coal heat production.

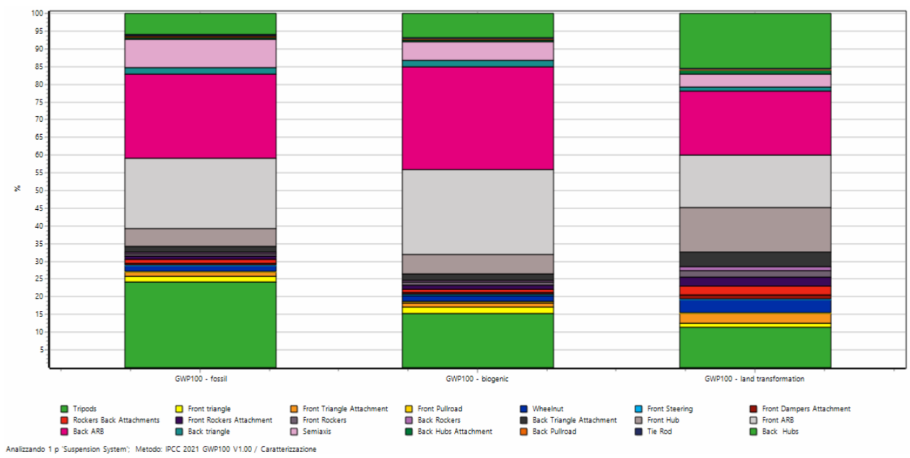


Figure 42: IPCC characterization GWP Suspension System

Regarding to this graph, the normalization shows that the indicators of global warming are practically the same according to the subsystems

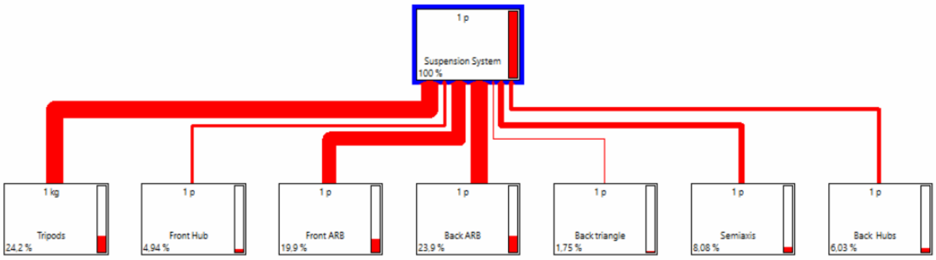


Figure 43: Process contribution grid Suspension System

The subsystems with the highest energetic contribution are tripods and front and back ARB (graphic with a higher than 2% of relevance).

ReCiPe 2016

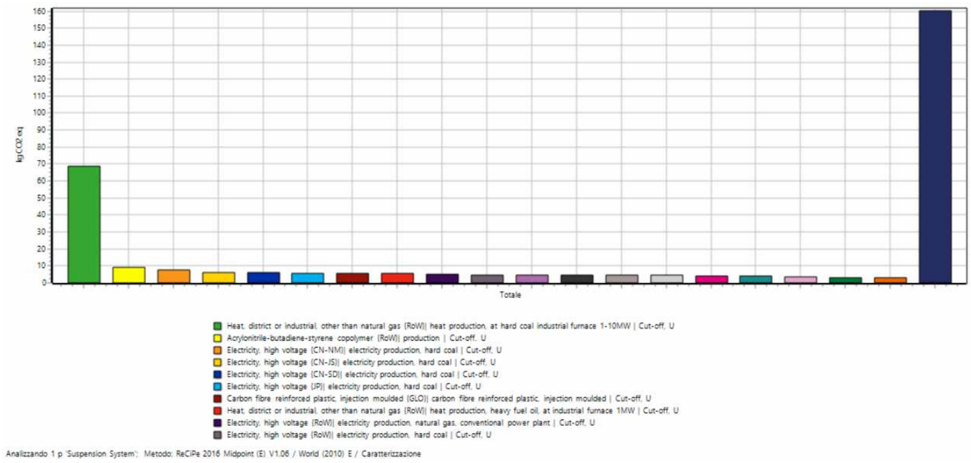


Figure 44: ReCiPe characterization Suspension System contributing process

The graph demonstrates the similarity in the indicator of global warming determined with the IPCC method.

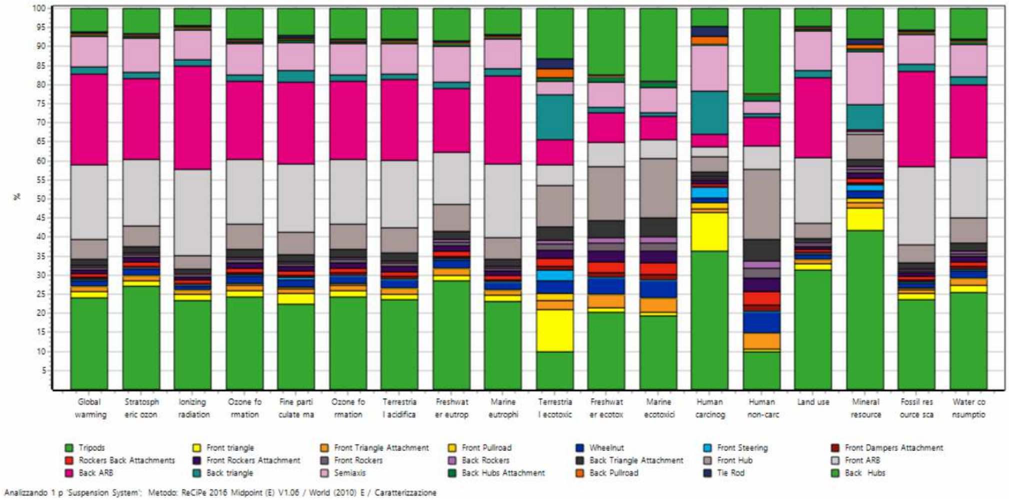


Figure 45: ReCiPe characterization Midpoint impact categories Suspension System

Regarding to the characterization for ReCiPe method, the highest contribution in all categories is due to the tripods, mainly composed by titanium. Special emphasis in the mineral resource category. Even though the weight of the tripods represents a 14% of the total weight for the Suspension System, the mineral resource due to tripods is higher than 50%. This is an indicator that titanium represent a high contribution in mining extraction.

6.3.2.6 Electrical System

IPCC 2021

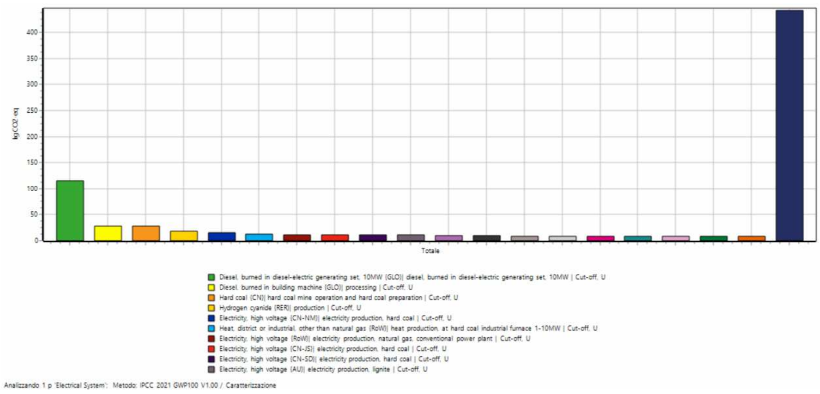


Figure 46: IPCC characterization Electrical System contributing process

The result is almost 450 kg CO_2 eq. which is quite relevant compared to the other systems, and the major precedence comes from hard coal heat production.

This result is really high compared to the ratio between the total weight of the car and electrical system (3,5%). A possible reason may be the higher use of copper and silver due to electronic components.

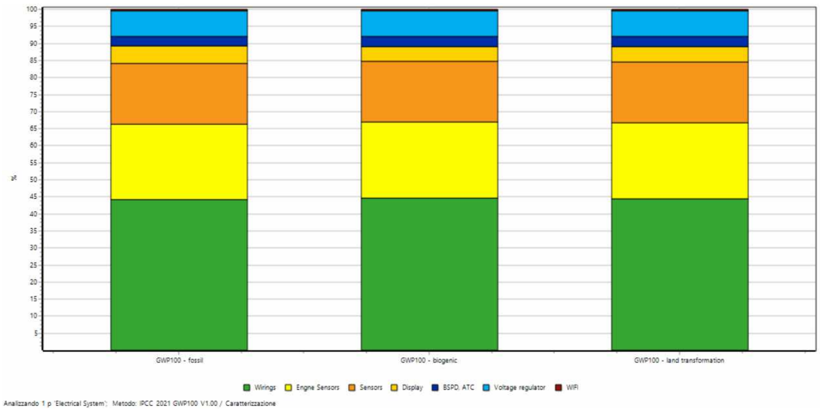


Figure 47: IPCC characterization GWP Electrical System

In this case, the percentage contribution in the 3 global warming categories is practically equal.

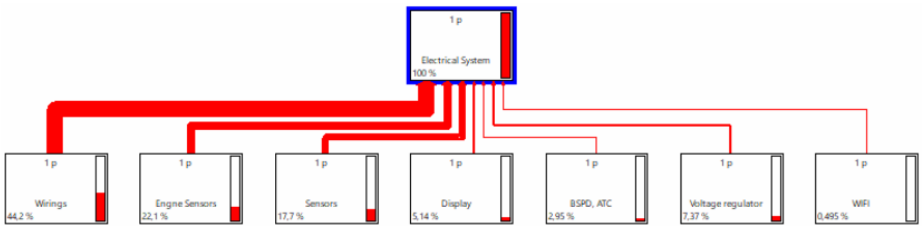


Figure 48: Process contribution grid Electrical System

The highest contribution in energy consumption is due to wirings and engine sensors. Other subcomponents are practically negligible.

ReCiPe 2016

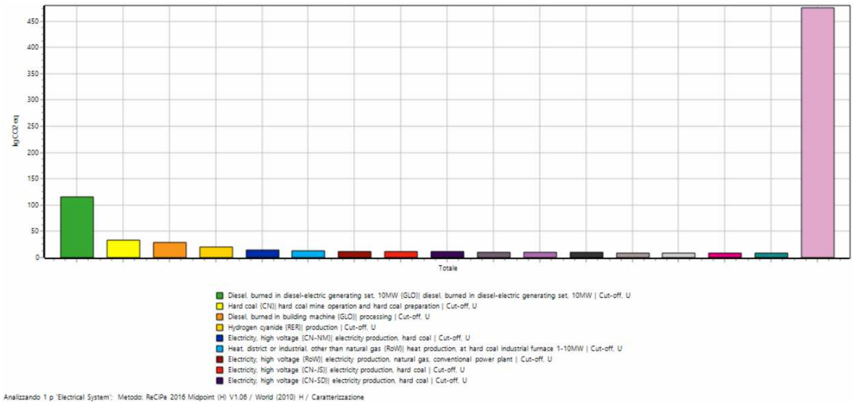


Figure 49: ReCiPe characterization Electrical System contributing process

This graphic shows the same result as ***Figure 46.***

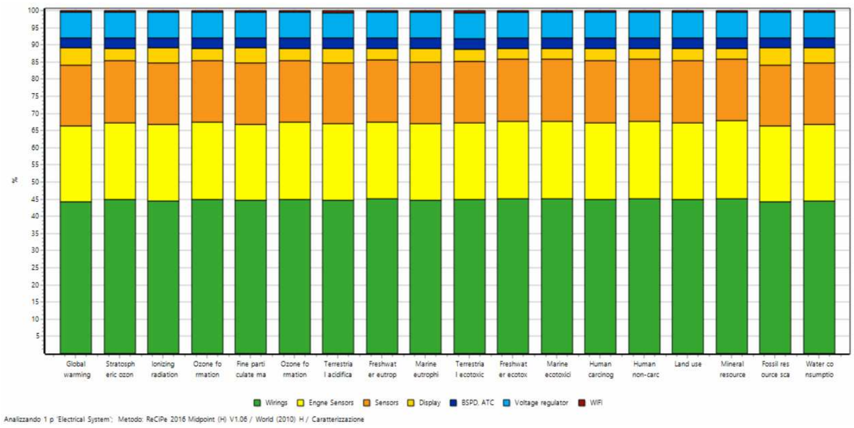


Figure 50: ReCiPe characterization Midpoint impact categories Electrical System

Regarding to this graphic, the result cannot be taken as valid because, as set in the scope, components done with different materials have the same relative mass for each material, so the result for the characterization becomes the same for each category.

6.3.2.7 Wheels and tyres

This subsystem is just divided in pneumatics and tires. It has been classified with a special subsystem because of the nomenclature of the precedent project.

IPCC 2021

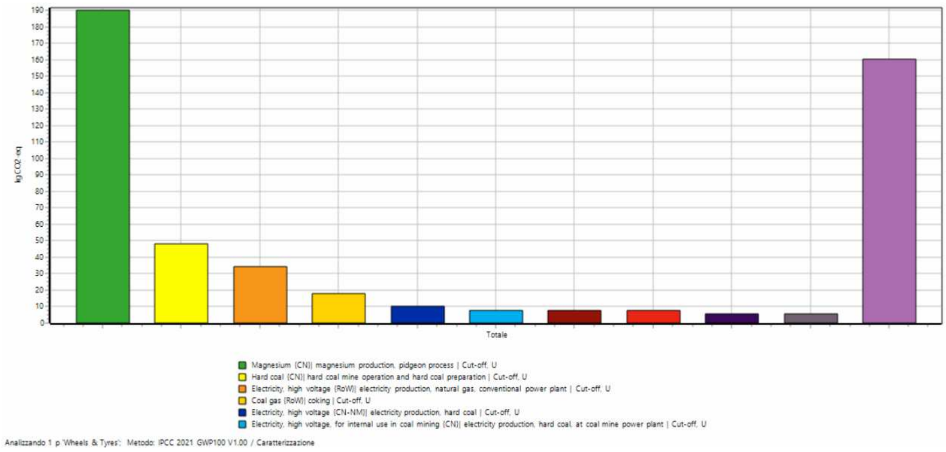


Figure 51: IPCC characterization Wheels and Tyres contributing process

ReCiPe 2016

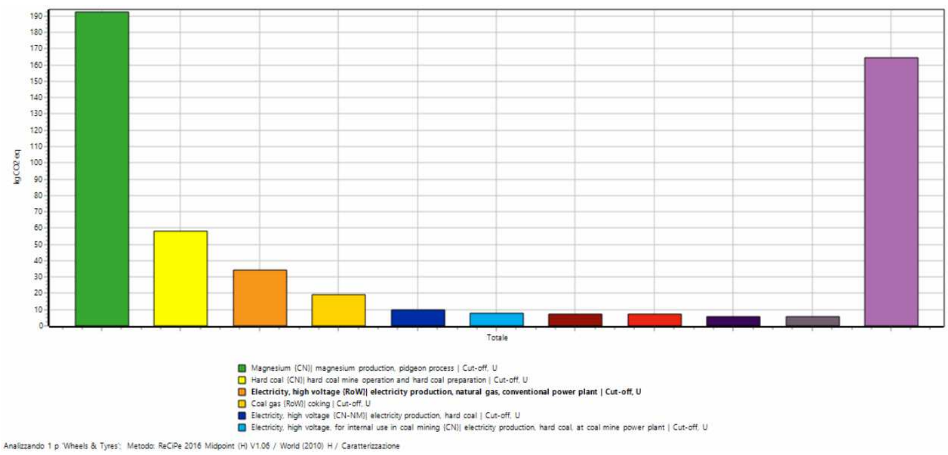


Figure 52: IPCC characterization GWP Wheels and Tyres

According to this, the unique result that must be taken into account is the total emission of 500 kg CO2 eq. and the highest contribution due to magnesium production, with 190 kg CO2 eq.

6.3.2.8 Other Components

IPCC 2021

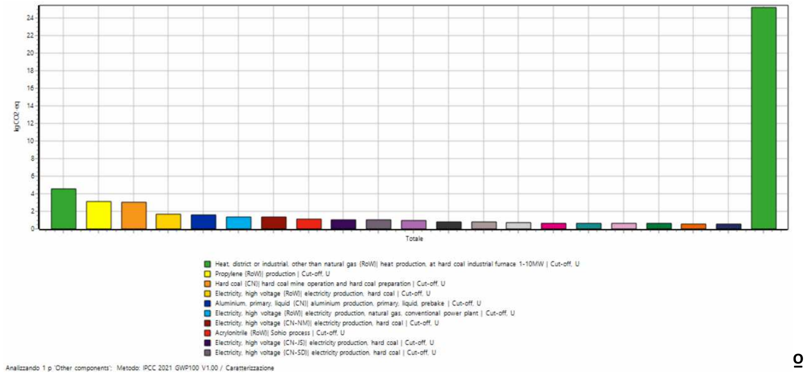


Figure 53: IPCC characterization Other Components contributing process

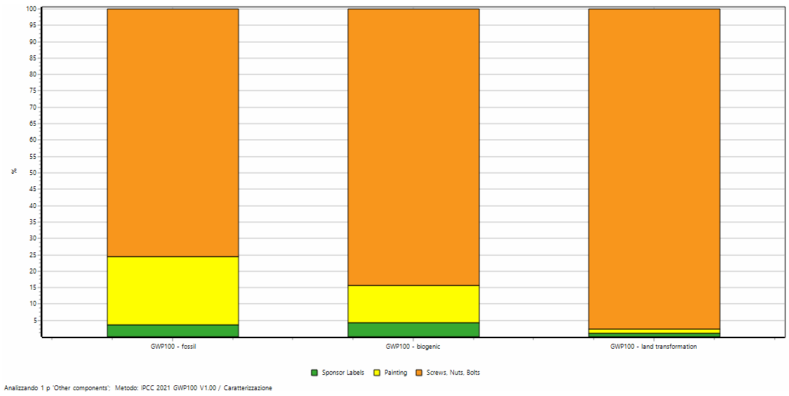


Figure 54: IPCC characterization GWP Other Components

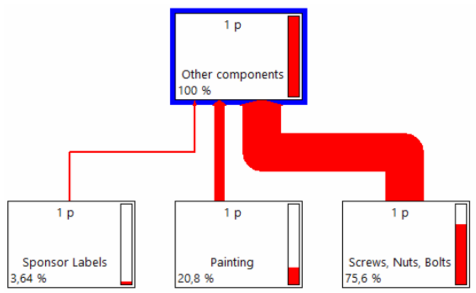


Figure 55: Process contribution grid Other Components

In the same line as the system wheels and tires, this category includes all components which does not belong properly to one of those mentioned. It has been also considered, as an estimation, the weight of screws, bolts and nuts used in the car. Total amount of GWP indicator is 25 kg CO2 eq.

6.3.3 Normalization

Normalization procedure, as the name indicates, compares the reference value obtained with a normal value, fixed for each category.

There is not just a unique way to determine those values. A possible method is quantifying the different values among a certain period of time, for example a year. Those values are preconfigured in SimaPro to facilitate the process.

In addition, with the normalization, we will be able to compare the results in later chapters with the previous car from 2013, although due to the evolution of the software and the different databases and impact categories, the comparison will not be fully reliable.

6.3.3.1 Frame and Body

ReCiPe 2016

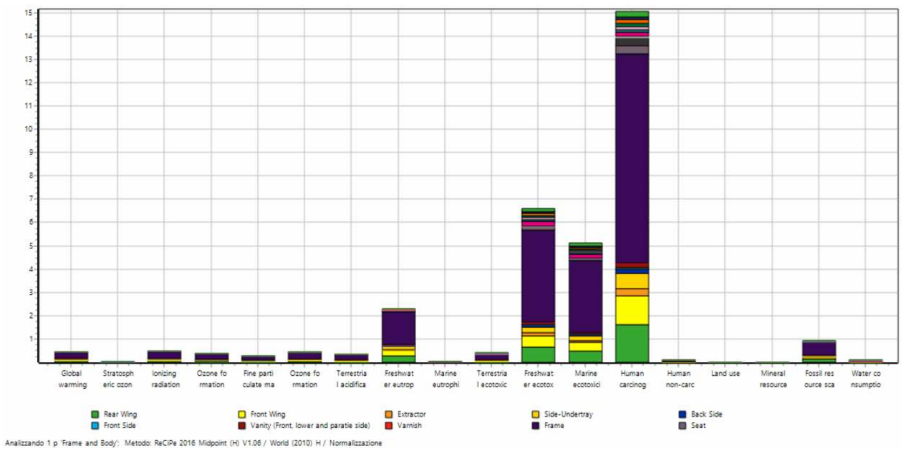


Figure 56: ReCiPe normalization impact categories Frame and Body

When normalization is done, is better seen the real importance of the categories of impact. In the case of the Frame and Body, the three most relevant impacts are Human carcinogen, freshwater ecotoxicity and marine ecotoxicity.

6.3.3.2 Engine and Drivetrain

ReCiPe 2016

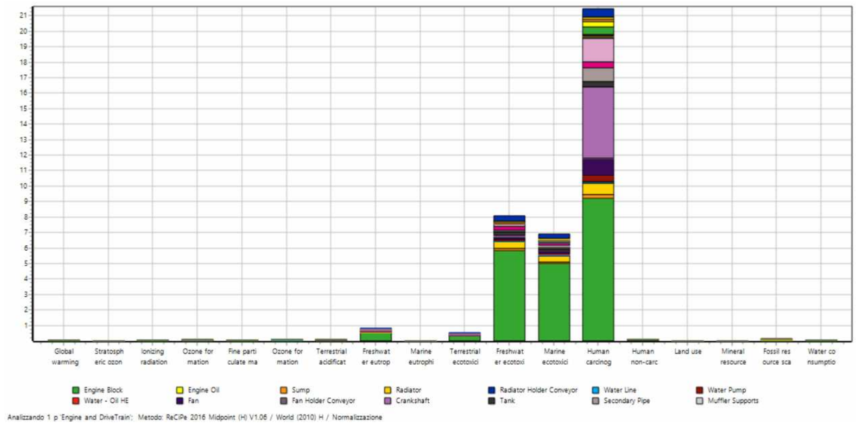


Figure 57: ReCiPe normalization impact categories Engine and Drivetrain

As in the previous case, the three most relevant impacts are Human carcinogen, freshwater ecotoxicity and marine ecotoxicity, with special relevance to human carcinogen.

6.3.3.3 Brake system

ReCiPe 2016

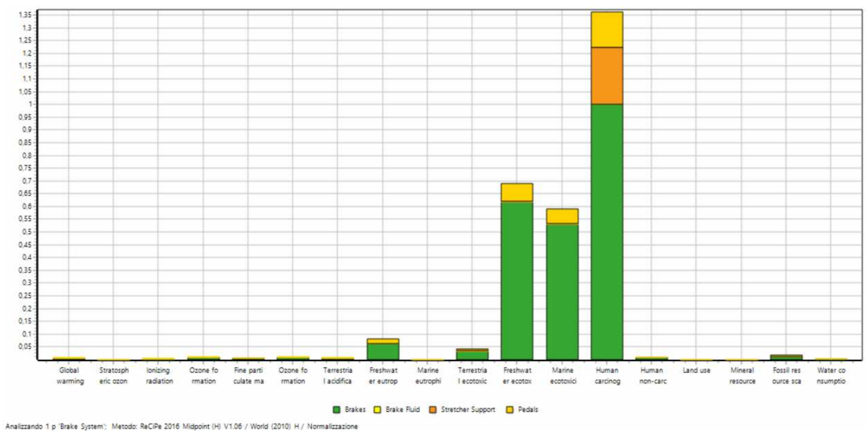


Figure 58: ReCiPe normalization impact categories Brake System

Following the same trend of the previous graphs, the normalization of the different categories gives more importance to the categories related to environmental and human toxicity.

6.3.3.4 Steering system

ReCiPe 2016

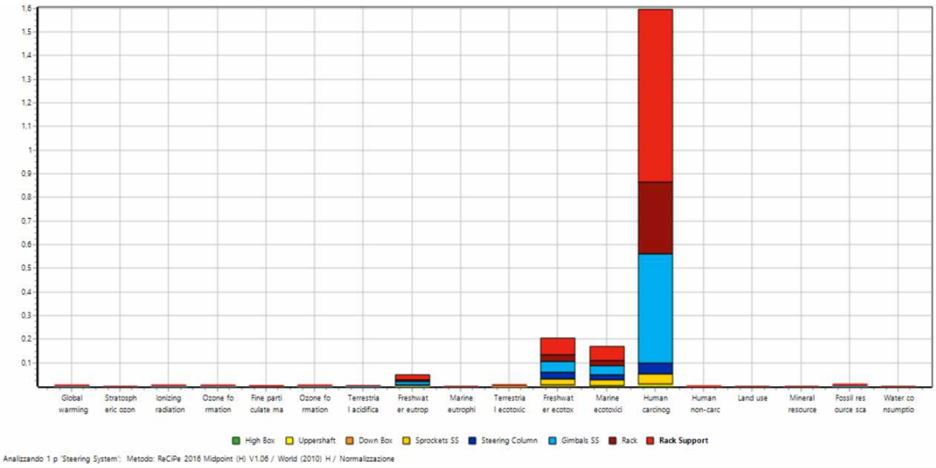


Figure 59: ReCiPe normalization impact categories Steering System

Idem to the previous graphs, with greater relevance in human carcinogen.

6.3.3.5 Suspension system

ReCiPe 2016

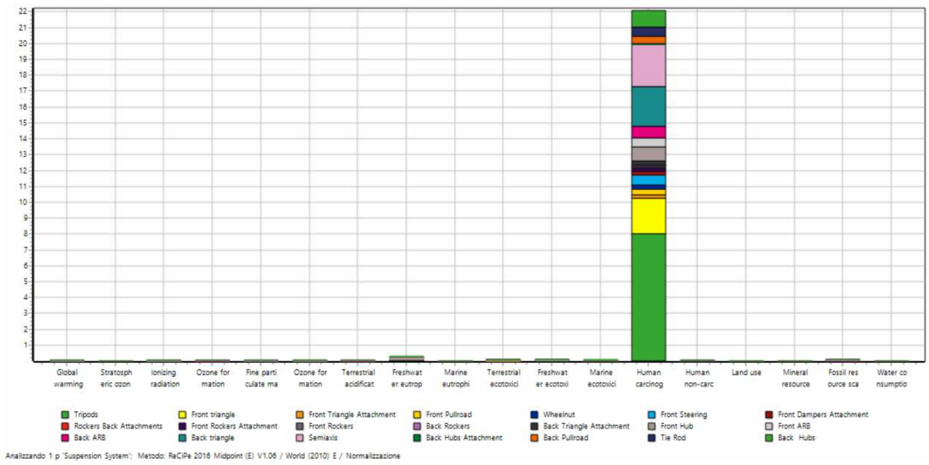


Figure 60: ReCiPe normalization impact categories Suspension System

The suspension system, composed mainly of stainless steel, aluminium and titanium, suggests, according to the previous graph, that the production of metals has a great impact on human health, much more relevant than any other category.

6.3.3.6 Electrical System

ReCiPe 2016

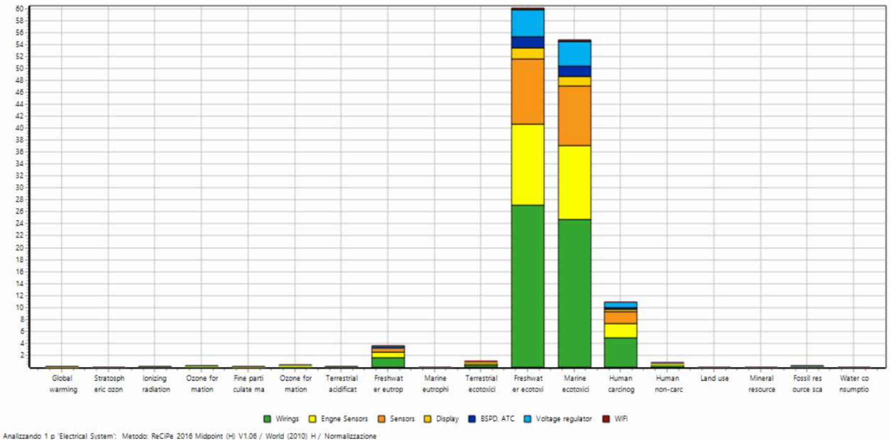


Figure 61: ReCiPe normalization impact categories Electrical System

In the electrical system we can appreciate a big difference: the categories that are most affected are those related to the toxicity of the water, both in seawater and freshwater. This is probably due to the greater impact that plastic (PVC) has on the production of wiring and electrical instruments.

6.3.3.7 Wheels and tyres

ReCiPe 2016

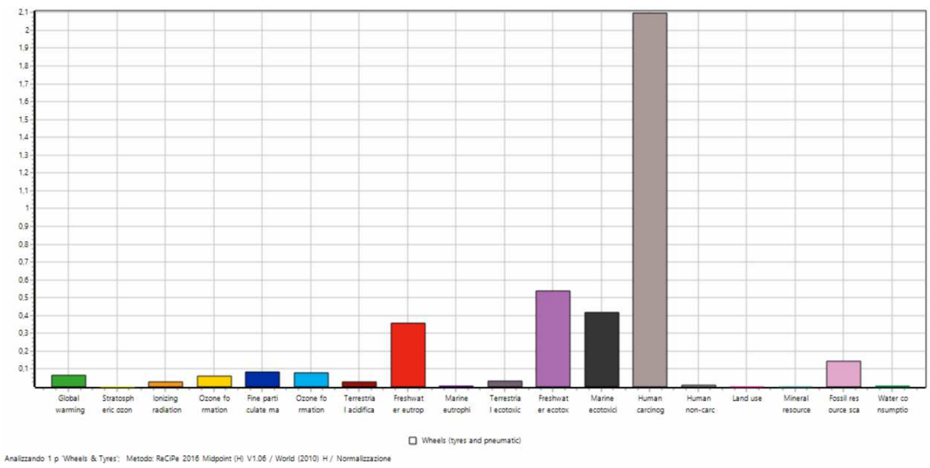


Figure 62: ReCiPe normalization impact categories Wheels and Tyres

6.3.3.8 Other components

For this category the results are not relevant, since they are an approximation and should not be taken into account.

6.4 Interpretation

At first, we could think that at least the use of minerals would have great importance in this project, since most of the car is made of aluminium and stainless steel.

However, the study suggests that the greatest impacts have to do with toxicity: either directly to humans in a carcinogenic form or directly exposed to the environment, in the form of contaminated water.

This second factor is directly due to the entire production industry that metals necessary for the manufacture of the car, which are included in processes collected in the SimaPro databases.

On the other hand, we realize that all the components made with carbon fibre also play a proven role in the most relevant impact categories, although the mass percentage is much lower. This behaviour was predictable, due to the high production toxicity of this material.

7. COMPARISON WITH PRECEDENT MODEL

According to the precedent model for the MG0712 developed for the Race Up Team in 2013, the evaluation method used for the preceding study is the Eco-indicator 99, which is the predecessor of the method used in this work, ReCiPe 2016.

In the old method, only three types of damage were distinguished in Endpoint: Human Health, Ecosystem Quality and Resources, however in Midpoint the set of impacts are as follows: carcinogen, resp. organics, resp. inorganics, climate change, radiation, ozone layer, ecotoxicity, acidification/Eutrophication, land use, minerals and fossil fuels, with the respective characterization units:

Impact category	Unit
Carcinogens	DALY
Resp. organics	DALY
Resp. inorganics	DALY
Climate change	DALY
Radiation	DALY
Ozone layer	DALY
Ecotoxicity	PAF*m2yr
Acidification/ Eutrophication	PDF*m2yr
Land use	PDF*m2yr
Minerals	MJ surplus
Fossil fuels	MJ surplus

Figure 63: Impact categories Eco-indicator 99

As can be seen, the characterization units are totally different from those currently used. For example, in fossil fuels category, the equivalence would be:

$$1\ kg\ oil\ eq \sim 10000\ kcal \sim 41000\ kJ$$

So for Frame and Body category, the result found in 2013 was 160,78 MJ surplus, and with the respective converting units:

$$160{,}78\ MJ\ surplus \cdot \frac{kg\ oil\ eq}{41\ MJ} = 3{,}92\ kg\ oil\ eq$$

Which differs a lot from the result obtained of approximately 902 kg oil eq. This result suggest that during this years, actualization of data must change the indicators references, and results cannot be compared.

Moreover, the unit DALY (Disability Adjusted Life Years) shown in ***Figure 63*** represents the number of disability years caused by the exposition to toxic material multiplied by this disability factor, which is a number from 0 to 1 that describes the severity of the damage (from 0 damage to fatal damage).

With all this previous reasoning, the quantitative comparison is ruled out, so a qualitative comparison is made through normalization, which is present in both studies.

We will start by comparing the Engine and Drivetrain system, with the following images:

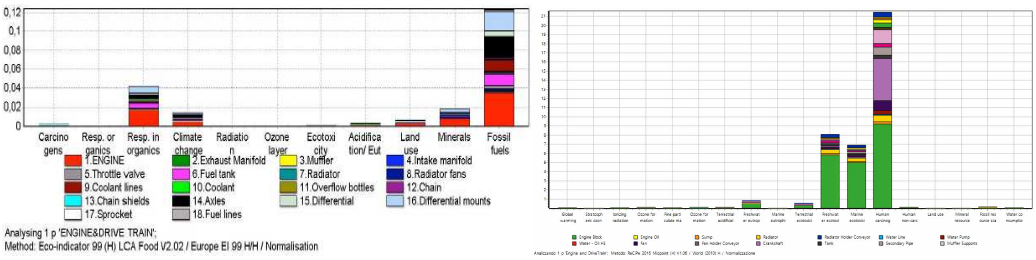


Figure 64: Comparison impact categories Eco-indicator 99 and ReCiPe 2016

This example will be useful to compare both trends, because all results obtained in the 2013th study are quite similar. While the normalization is based in a weighing, results obtained are totally different: while in 2013 fossil fuels was representing the 12% of the total damage, nowadays represents less than a 0,5%.

However, the most representative category currently, human carcinogen, which represents 21% of the normalized impact, in 2013 it did not represent more than 2%.

Finally, regarding to climate change, the percentage in 2013 was close to 10%, while now it is much less than 1%.

8. CONCLUSIONS

The objective of this thesis, as defined in section 5.1, was to determine which systems and components produce the greatest environmental impact, and as a result, take the appropriate measures for possible modifications to reduce this impact.

Following this thread, we have observed that carbon fiber-based components have a great impact on environmental and human toxicity: high rates of Human carcinogen are present in all subsystems. Other materials that generate this high toxicity in a similar way are metals such as aluminium and stainless steel.

On the other hand, we have been able to observe that, unlike its family of metals, titanium has a high impact on Mineral Resources, so that the extraction of titanium really generates a high environmental impact.

As expected, the components with higher mass percentages are those that contribute more to the different impact categories. This is due, on the one hand, to the fact that handling processes for these materials have not been included and, therefore, it is their extraction as raw material that is computed in this analysis.

In practically all systems, the heat production process using coal is the one that generates the most GWP. This fact was also predictable, since high temperatures are required to work metals and many fossil resources are used for this.

With regard to the comparative analysis with the previous model, little can be said, since either the indicators of the different impact categories have changed, or the standards and databases have been updated, so that practically for a decade, sustainable development has focused more on environmental and human toxicity than on the fossil resources themselves.

To conclude, I would like to make special mention of the data collection phase. A priori it may seem like a simple task, but during the realization of this project I have been able to realize that it really is the phase that requires the most resources and time. It is true that with more time and greater cooperation with the Race Up team, much more detailed results could have been obtained, but the limitation of time has been the conditioning factor for this project.

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10. ANNEX

10.1 ANNEX I – Data collecting provided by RaceUp Team

In this first annex it is included the summarizing table of all data collected:

System	Subsystem (ENG)	Material	MG15 Weight (g)
Frame & Body	Rear Wing	CFRP	5651
	Front Wing	CFRP	4200
	Front Wing	CFRP	120
	Side-Undertray	CFRP	2300
	Extractor	CFRP	1000
	Back side	CFRP	650
	Front side	CFRP	250
	front, lower and paratie side	CFRP	600
	Paint	Acrilic Paint	1200
	Frame	Monocoque (CFRP + Aluminum Honeycomb (20%))	32000
	Seat	CFRP	1200
	Head-rest	Foam	215
	Belt Fastening	Stainless Steel	400
	Seat Attachment	Stainless Steel	36
	SidePOD	CFRP	150
	Wheel	CFRP + Electronics Cables/Connectors	550
	Quick Release Steering Wheel	Aluminum	500
	Anti Intrusion Plate	4mm Aluminum Plate	500
	Impact Attenuator	Honeycomb Aluminum - extruded	700
	Firewall	Aluminum Foil (0.5mm)	630
	Front Wing Support	Al	400
	Rear Wing Support	Al	900

Engine & Drivetrain	Engine Block	Al	36000
	Sump	Aluminum	900
	Oil Motor	Oil	3000
	Fly-wheel housing	Aluminum	542
	Line Fuel	Misto teflon, acciaio, aluminum	150
	Airbox	CFRP	800
	Throttle butterfly	Aluminum & bronze	88
	Desmodromic gearbox	Acciaio	173
	Dog Rings	Stainless Steel	427
	Gears	Stainless Steel	1505
	Radiator (Full)	Aluminum	2770,6
	Radiator Holder conveyor	Aluminum	41,82
	Water line	Aluminum & Silicon Tubes	787,79
	Rubber hoses	Rubber	300
	Water in line	Water	1500
	Water pump	Stainless Steel	400
	Water - Oil Heat Exchanger	Copper & Aluminum	50
	Fan	Aluminum, Stainless Steel	1946
	Fan holder conveypr	CFPR	150
	Crankshaft	Stainless Steel	5380
	Tank	Aluminum	1507
	Fuel	E85	5809
	Secondary Pipe	Titanium & Carboceramin Coating	490
	Muffler supports	Aluminum	90
	Pistomn engines	Aluminum	1324
	Screws	Aluminum	66
	Tripod Houses	Titanium	417
	Tripod Houses	Titanium	449

	Sprockets	Stainless Steel	145
	Gear-wheel	Aluminum	222,2
	Gear-wheel Supports	Al	268
	Chain drive	Stainless Steel	596
	Chain guard	Stainless Steel	440
	Bearings	Stainless Steel	186
	Differential Mount	Al	556
	Differential	Al	2000
	Oil Differential	Oil	200
Brake System	Brakes	Al	3782
	Brake Fluild	Oil	300
	Stretcher support	Stainless Steel	270,81
	Pedal	CFRP + Al	500
Steering System	High Box	3D printed Al	414,88
	Uppershaft	3D printed Al	167
	Down Box	3D printed Al	192
	Sprockets	Al	165,15
	Steering column	Al	115
	Gimbals	Titanium	268
	Rack	Titanium	175
	Rack Support	Titanium	42
Suspension	Front triangle	Stainless Steel	1131,98
	Front Pullroad	St	197,76
	Front steering	St	229,36
	Front Hub	Aluminum	1307,2
	Wheelnut	Aluminum (anodised)	192
	Front dampers attachment	Al	110
	Rockers Front Attachments	Al	260
	Front Rockers	Al	130

	Front triangle attachment	Al	416
	Anterior ARB	CFRP	1000
	Back triangle	Stainless Steel	1250,82
	Back pullroad	St	238,56
	Tie Rod	St	268,43
	Back Hubs	Aluminum	1595,2
	Wheelnut	Aluminum (anodised)	192
	Back Hubs Attachment	Al	120
	Back Rockers Attachment	Al	260
	Back Rockers	Al	180
	Back triangle Attachment	Al	296
	Back ARB	CFPR	830
	Semiaxis	Titanium	600
	Tripods	Titanium	1800
Electrical System	Wirings	Copper, Aluminum, Silver, PVC	3000
	Engine Sensors	Copper, Aluminum, Silver, PVC	750
	Sensors	Copper, Aluminum, Silver, PVC	1200
	Radio	N.A.	0
	Display	Raspberry + Plastic Support - CFRP Dashboard	500
	BSPD, ATC	Copper, Aluminum, Silver, PVC	200
	Voltage regulator	Copper, Aluminum, Silver, PVC	500
	Wifi	Copper, Aluminum, Silver, PVC	78
Wheels & Tyres	5.5kg (each, 4 total)	Magnesium + rubber (4.3 kg magnesium - 1.2 kg rubber)	22000
Other Components	Sponsor labels	-	500
	Screws, nuts, bolts	Al	3000
	Painting	Acrylonitrile	1000