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SIMPLIFIED LIFE CYCLE ASSESSMENT OF A MECHATRONIC SYSTEMS: APPLICATION TO A REGENERATIVE BRAKING SYSTEM

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Abstract:

Life Cycle Assessment (LCA) is a standardized method for assessing the environmental impacts of a product, as defined by ISO 14040:2006 and ISO 14044:2006. It allows the environmental footprint of a product to be calculated for all the different stages of its life cycle (raw material extraction, manufacturing, transport, use and end of life) based on a set of representative product environmental indicators (climate change, natural resources, ozone, toxicity, Eco toxicity...). Conducting a life cycle assessment (LCA) requires the processing, the calculation, and the analysis of a wide range of information. The use of LCA software facilitates these different phases, guaranteeing transparency and traceability. In this study, a simplified LCA is carried out for a mechatronic system, which is a regenerative braking system, especially for production phase. CML baseline 2000 method was used for the life cycle impact assessment using Open LCA software. The purpose of this study is to quantify the environmental impact associated with the production of a regenerative braking system and to pinpoint the environmental hotspots across the individual components and links constituting such systems.

Index Terms: Eco-design, Life cycle assessment, Simplified LCA, design for environment**,** mechatronic systems environmental assessment, Open LCA, environmental hotspot, CML Baseline.

1. INTRODUCTION

Industry, mass consumption and the increased energy needs of a growing world population are partly responsible for the environmental damage the planet is suffering. Globalisation has gone hand in hand with these developments, and as a result, contributes to the observed increase in environmental damage [1]. It has allowed material goods to be produced, exchanged, and consumed in volumes and at rates that humanity had never experienced before. This fact has accentuated the ecological footprint [2] of human activities all over the world. Today, environmental protection is becoming an increasingly important issue in global political debates. Climate change, waste management problems, deforestation and biodiversity losses are causing public alarm. Over the last few decades, measures have gradually been adopted in industrialised countries to address these concerns. These measures aim to reduce the negative effects of industrial development through sustainable development, i.e., a mode of development that combines economic, social, and environmental aspects to satisfy the current generation's needs without endangering the ability of future generations to fulfil their own needs[3]. Reducing the negative impacts of human activity is the responsibility of all actors involved in motivating and organising product systems (governments, consumers, and industries). Companies have the greatest responsibility, because they both structure consumption patterns and generate production patterns through their specifications. Today, companies are under pressure from customers, competition, and legislation, encouraging them to become more involved in environmental efforts and to take concrete and sustainable actions.

Based on the above-mentioned facts, the idea that methods and techniques should be designed following the concept of sustainability [4] has gained importance. This perspective envisages a holistic assessment of all upstream and downstream effects of human activity or product manufacture, in order to assess cumulative and synergistic effects on the environment in space and time. Among those methods and approaches we can site, the mono criteria approach [16], which is specifically designed to analyse a single environmental factor over the entire life cycle. The matrix approach [5] used to carry out the environmental assessment of a product. For example, The NF-Environment evaluation grid [6], can be used to evaluate the overall impact (evaluated in Milli points) from the various sources of impact (material and energy consumption, transported mass, end-of-life scenario, etc.). This tool resembles environmental rating tables for each material and process. The qualitative approach [24]: necessary to understand how people and communities experience and act on environmental problems .The check lists [25]: this Environmental Assessment and Improvement tool in the form of a questionnaire helps to guide the design towards a less impactful solution. The LCA [26] is considered as one of the most internationally accepted methods for examining the global impact on the environment.

In the following, as a first instance, the section 2 describes the materials and methods to be used including mechatronic systems description and a deeper life cycle assessment methodology definition. Afterwards, in section 3 the sequential approach of the studied system's life cycle assessment, involving the definition of objectives, the inventory of emissions and extractions, the impact assessment and their interpretation are thoroughly discussed. Ultimately, section 4 presents some conclusions and further perspectives of this work.

2. MATERIALS AND METHOD

In further steps, the Mechatronic System is considered a combination of components, which are interconnected through a set of links.

2.1 Mechatronic system description

A Mechatronic system is a complex multi-component and multi-technology-based product. It is, hence, an assemblage of various components from different technologies and features (mechanical, electronic, software, etc.) linked by a variety of links (mechanical, functional, flow exchange) .The French standard NF E 01-010 (2008) defines mechatronics as an "approach to the synergistic integration of mechanics, electronics, automation and computing in the design and manufacture of a product to increase and / or optimize its functionality" [7] .

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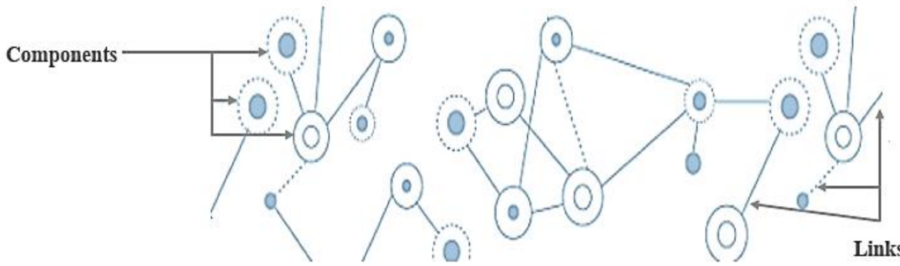
Fig 1: Mechatronic system



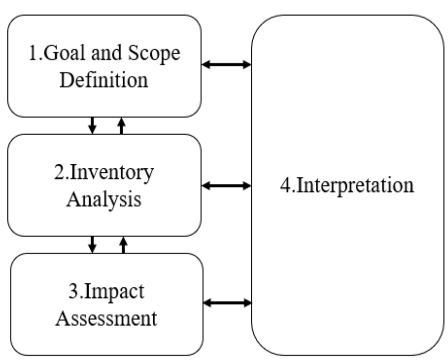
Then, a Mechatronic product can be seen as a network of components inter-connected by links and collaborating to achieve a given objective Fig: 1

2.2 Life cycle assessment and simplified life cycle assessment

Life cycle assessment (LCA) is a method developed since the end of the 1960s [8], with the aim of estimating the environmental impact of a product or a process by quantifying, throughout its life cycle, the materials, energy, and waste flows and converting them into potential environmental impacts which will permit to set action priorities. Today and since the 1990s, the method has been developed mostly through SETAC (Society of Environmental Toxicology And Chemistry) and the JRC (Joint Research center) [12].This tool is regulated by the following ISO standards: ISO 14 040 [9] and Iso 14 044 [10][11].

The method is an iterative process, implying that it is possible at any stage to go back to the previous steps in order to refine or detail them:

Fig 2: LCA steps according to ISO 14040 [9]



- Goal and scope definition: This stage is essentially descriptive; it allows the motivations and objectives of the study to be clarified, and the system studied and its limits to be described, upon which will depend the choices to be made in the rest of the study.

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- Life cycle inventory analysis: The extraction and emission inventory are the accounting of material and emission flows that cross the system boundary.
- Life cycle impact assessment: this phase translates the inventory values into a reduced number of potential impacts (greenhouse effect, atmospheric acidification, human health, etc.) to ease interpretation. Various methods exist to provide impact indicators reflecting the potential environmental impact of substances emitted from the system [17]. The term "potential" is important because it does not refer to a real measured impact. In general, impact assessment is carried out in three stages. The first two are systematic: classification, then characterisation. A third step is optional, the evaluation [10]. Classification: allows inventory flows that contribute to the same environmental impact (greenhouse effect, eutrophication, acidification, etc.) to be grouped together in the same category, eutrophication, acidification, etc.).Characterisation: quantifies the contributions of the different flows to the potential impacts. The emissions and extractions within each category are weighted via characterisation factors. Evaluation: consists of 3 optional steps, due to their not purely scientific and subjective character subjective: Standardisation, Grouping and weighting [9].
- Results interpretation analyses the findings of the previous step, allows conclusions to be drawn and outlines the limitations of the study.

Simplified LCA (i.e., streamlined LCA) was developed to efficiently assess the life cycle environmental factors of a product, process or service and deliver the same kind of results as a detailed LCA [14]. Simplified LCA can incorporate simple input/output analyses or hybrid analyses but may also involve a horizontally limited approach by neglecting certain stages of the life cycle [17].

3. APPLICATION

The system under examination is a regenerative braking system Fig.3. Regenerative braking extracts kinetic energy, from the wheels, that is lost in the form of heat and friction during conventional braking. It is most effective for vehicles moving at higher speeds. In essence, during regenerative braking, the kinetic energy of the driving wheels is converted by the electric motor - which functions as a generator for this purpose - into electrical energy. In this way, some of the energy that is normally lost as frictional heat during braking is transferred as electrical energy to the battery and battery pack [15].

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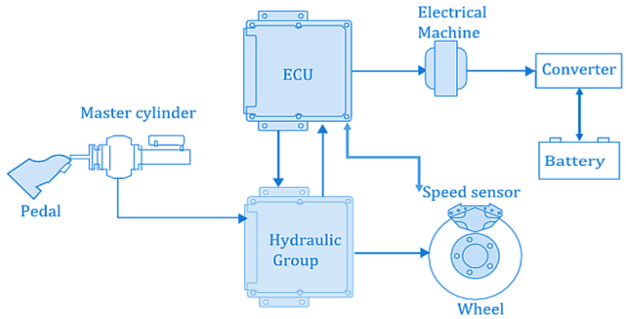
Fig 3: Regenerative braking system



We suggest carrying out a simplified LCA, focusing on production phase, of a regenerative braking system mechatronic including their components and the links between them.

3.1 Goal and scope definition

The goal of this study is to evaluate the potential environmental impact associated with each component and link of the regenerative braking system presented in fig.3 during production phase of the life cycle. The intended audience of this study are researchers, policymakers, and practitioners of LCA.

The scope of the study includes the function of the system, functional unit, and system boundaries. The function of this system is to break with energy recovery. We mention in tables 1 and 2 below, the list of components and links forming the system:

Table 1: Components List

Component	Type
Pedal	Mechanical
Master Cylinder	Mechanical
Hydraulic Group	Mechanical
Reservoir	Mechanical
Electrical Machine	Mechanical
Disc	Mechanical
Caliper	Mechanical
Brake Pad	Mechanical
Tyre	Mechanical
Speed Sensor	Electrical
DC-DC Converter	Electrical
Battery	Electrical
ECU	Electrical/Software

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Table 2: Links List

Link	Description	Type
L_{P_MC}	Pedal and master cylinder	Mechanical
L_{MC_HG}	Master cylinder and hydraulic group	Hydraulic
L_{MC_R}	Master cylinder and Reservoir	Mechanical
L_{MC_C}	Master cylinder and caliper	Mechanical
L_{HG_C}	Hydraulic group and caliper	Mechanical
L_{HG_MC}	Hydraulic group and master cylinder	Mechanical
L_{EM_D}	Electrical machine and disc	Mechanical
L_{EM_DCC}	Electrical machine and DC converter	Electrical
L_{EM_ECU}	Electrical machine and control unit	Electrical /Software
L_{D_BP}	Disc and brake pads	Mechanical
L_{C_BP}	caliper and brake pads	Mechanical
L_{SS_ECU}	Speed sensor and control unit	Electrical /Software
L_{T_EM}	Tire and Electrical machine	Mechanical
L_{DCC_EM}	DC converter and Electrical machine	Electrical
L_{DCC_ECU}	DC converter and battery	Electrical
L_{DCC_B}	DC converter and control unit	Electrical /Software
L_{B_DCC}	Battery and DC converter	Electrical
L_{B_ECU}	Battery and control unit	Electrical /Software
L_{ECU_EM}	ECU and electrical machine	Electrical /Software
L_{ECU_T}	ECU and tyre	Electrical /Software
L_{ECU_B}	ECU and Battery	Electrical /Software
L_{ECU_DCC}	ECU and DC Converter	Electrical /Software

The system boundaries clarify which processes should be included or excluded from the study. The system boundaries should be defined in a way that is consistent with the purpose of the study.

The system boundaries for this study were considered after a thorough review of the literature, expert advice, and limitations in the availability of process data. The system boundaries chosen for this study are the production phase of the regenerative braking system including the components and the links mentioned in Table 1 and 2.

3.2 Life cycle inventory analysis (LCI)

The inventory is carried out using the Open LCA software. An inventory workbook was developed to record the data. The fig .4 illustrates an input inventory for the lead-acid battery as an example. The data from the manufacturers were used as much as possible. Where such data was unavailable, the following were used:

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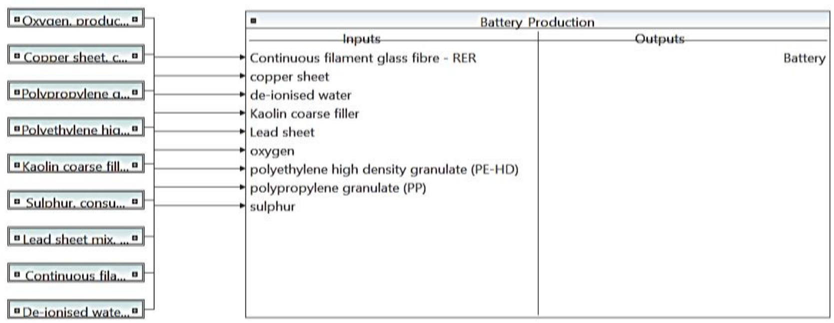
- Data from the specialized literature, systematically validated by experts,
- The Open LCA database.

Fig. 4.Example of LCI-Battery, Open LCA software

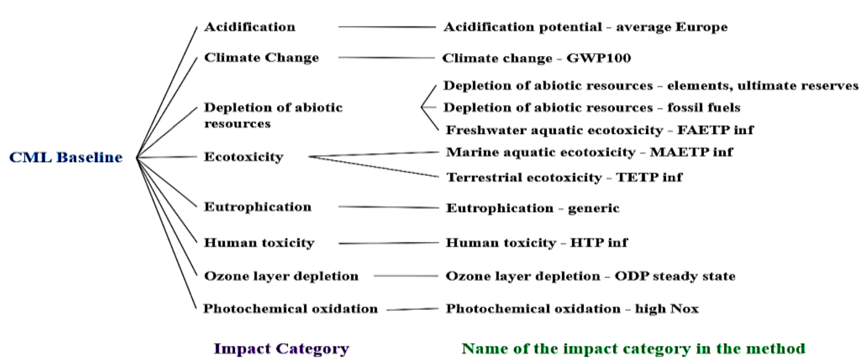


Data quality assessment is important when reporting LCA results. As in [27], a table is used to reference and qualify all data to offer a good overview of their strengths and weaknesses and to allow their use in the assessment phase. The inventory is qualified with the terms "good", "average", or "poor" accordingly.

3.3 Life cycle impact assessment (LCIA)

During this phase, the quantity and the intensity of potential environmental impacts derived from the LCI are identified and evaluated. The potential environmental impacts were computed using the standard impact assessment methods of the Open LCA software. For this study, the CML Baseline 2000 impact assessment method is employed. The Center for Environmental Sciences (CML), University of Leiden, Netherlands, developed the CML Baseline 2000 methodology [32]. CML Baseline 2000 scores each impact category separately and thus helps to identify the potential impacts of each category. The following impact categories are considered consistent with ISO 14044:

Fig. 5.CML Baseline



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The outcome of this study is based on actual data collected from experts and on available data. The life cycle impact assessment of RBS using the chosen impact assessment methodology is reported in Fig.6 and Fig.7:

Fig 6: Components simplified LCA results

LCA results-Components	Pedal	Master Cylinder	Hydraulic Group	Reservoir	Electrical Machine	Disc	Caliper	Brake Pad	Tyre	Speed Sensor	DC-DC Converter	Battery	ECU
Acidification potential - average Europe	0,003921629	0,004961911	0,00913268	0,003248306	0,001121511	0,036814136	123,95309	0,001047553	319026,012	0,014346945	7,55E-05	0,100734445	0,00198681
Climate change - GWP100	1,907919554	1,105637281	3,049266868	0,716384147	0,398261391	8,119020331	45788,77646	0,35974864	117849487,1	4,291036367	0,032058292	24,2422666	0,324806469
Depletion of abiotic resources - elements, ultimate reserves	-3,43E-06	2,90E-07	-4,15E-06	2,23E-07	3,50E-06	2,53E-06	-0,35633903	6,74E-06	-917,132335	1,15E-05	2,18E-09	0,004160631	9,00E-05
Depletion of abiotic resources - fossil fuels	19,3759122	11,79456902	30,83166077	8,11795401	4,372870429	92,00347878	509239,0448	4,07336466	1310660903	56,73810662	0,910602182	452,3394208	4,003246915
Eutrophication - generic	0,000442683	0,000268528	0,000629585	0,000210224	0,00403062	0,002382544	13,47076084	0,009300967	34670,5543	0,001932521	7,47E-06	0,01055941	0,000163927
Freshwater aquatic ecotoxicity - FAETP inf	0,001969768	0,003817947	0,001627109	0,002199808	0,000409371	0,024931154	39,26512901	0,000433914	101059,5266	1,966987154	0,049057476	2,626755701	0,144624899
Human toxicity - HTP inf	0,09445107	0,644404295	0,037093973	0,328986346	0,01818231	3,728511916	2041,746724	0,015915694	5254973,296	10,74675545	0,016521698	6,615502986	0,118812784
Marine aquatic ecotoxicity - MAETP inf	2,634378868	1977,455232	4,050182578	1019,538908	58,59517413	11554,77429	6810286,811	35,31207381	17528068739	209,895135	36,07598276	2049,866781	291,3390757
Ozone layer depletion - ODP steady state	0	1,23E-07	0	8,55E-08	2,25E-07	9,69E-07	0,001017847	5,18E-07	2,619698351	9,44E-09	7,41E-10	1,13E-07	2,66E-08
Photochemical oxidation - high Nox	0,00088565	0,000263901	0,001351252	0,000172459	0,000162396	0,001954533	20,95958144	0,000124216	53945,00606	0,000960576	1,26E-05	0,006031928	0,000147902
Terrestrial ecotoxicity - TETP inf	0,02150033	0,00277197	0,018367102	0,001542827	0,001379328	0,017485377	90,32784278	0,002122766	232482,5569	0,015881042	0,00668029	0,166578519	0,048549593

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Fig. 7: Links simplified LCA results

LCA results-Links	L_{P_MC}	L_{MC_HG}	L_{MC_R}	L_{MC_C}	L_{HG_C}	L_{HG_MC}	L_{EM_D}	L_{EM_DCC}	L_{EM_EC}	L_{D_BP}	L_{C_BP}	L_{SS_ECU}	L_{T_EM}	L_{DCC_E}	L_{DCC_B}	L_{DCC_EC}	L_{B_DCC}	L_{B_ECU}	L_{ECU_EM}	L_{ECU_T}	L_{ECU_B}	L_{ECU_DCC}
Acidification potential - average Europe	0,01083	0,00224	0,00039	0,00069	0,00084	0,00224	0,05414	0,02138	0,02031	0,00208	0,00297	0,01037	0,00069	0,01113	0,00223	0,01213	0,00277	0,01213	0,02031	0,01037	0,01213	0,01213
Climate change - GWP100	2,38795	1,02627	0,19079	0,25258	0,28517	1,02627	11,9397	5,16533	5,38181	0,51989	1,04149	2,41822	0,25258	2,41952	0,4839	3,1652	0,71205	3,1652	5,38181	2,41822	3,1652	3,165199
Depletion of abiotic resources - elements, ultimate reserves	7,4E-07	6,2E-07	-3E-07	5,7E-06	5,8E-06	6,2E-07	3,7E-06	0,0003	0,00011	5,5E-05	-2E-06	3,9E-05	5,7E-06	3,6E-05	7,1E-06	6,9E-05	1,7E-05	6,9E-05	0,00011	3,9E-05	6,9E-05	6,93E-05
Depletion of abiotic resources - fossil fuels	27,0598	10,5883	1,93759	2,57962	3,14687	10,5883	135,299	75,8481	100,624	6,36039	10,5181	38,9188	2,57962	37,7775	7,55551	56,9239	12,3263	56,9239	100,624	38,9188	56,9239	56,92391
Eutrophication - generic	0,0007	0,00027	4,4E-05	6,1E-05	7,1E-05	0,00027	0,0035	0,0035	0,01243	0,00014	0,00028	0,00447	6,1E-05	0,0043	0,00086	0,00815	0,00201	0,00815	0,01243	0,00447	0,00815	0,008147
Freshwater aquatic ecotoxicity - FAETP inf	0,00733	0,00086	0,0002	0,00027	0,18826	0,00086	0,03666	0,93678	22,8135	0,00457	0,00047	0,68632	0,00027	9,4007	1,88014	12,0077	2,40168	12,0077	22,8135	0,68632	12,0077	12,0077
Human toxicity - HTP inf	1,09662	0,0293	0,00945	0,01265	1,04056	0,0293	5,48311	5,47256	124,804	0,08992	0,02134	3,80507	0,01265	51,4559	10,2912	65,7121	13,1485	65,7121	124,804	3,80507	65,7121	65,71208
Marine aquatic ecotoxicity - MAETP inf	3398,46	140,117	0,26344	60,1732	62,4636	140,117	16992,3	980,914	1168,35	138,457	1,134	426,983	60,1732	451,338	90,2676	756,739	185,029	756,739	1168,35	426,983	756,739	756,7386
Ozone layer depletion - ODP steady state	2,9E-07	1,9E-09	0	3E-09	3E-09	1,9E-09	1,4E-06	2,5E-07	2,8E-07	4E-08	0	9,4E-08	3E-09	9,4E-08	1,9E-08	1,9E-07	4,7E-08	1,9E-07	2,8E-07	9,4E-08	1,9E-07	1,89E-07
Photochemical oxidation - high Nox	0,00057	0,00042	8,9E-05	0,00011	0,00012	0,00042	0,00287	0,00132	0,00129	0,00013	0,00046	0,00063	0,00011	0,00063	0,00013	0,00076	0,00017	0,00076	0,00129	0,00063	0,00076	0,00076
Terrestrial ecotoxicity - TETP inf	0,00514	0,00142	0,00215	0,00037	0,00049	0,00142	0,02571	0,32039	0,0063	0,0625	0,00538	0,00637	0,00037	0,00697	0,00139	0,00362	0,0008	0,00362	0,0063	0,00637	0,00362	0,003619

Results interpretation and discussion

Fig.8 and Fig.9 illustrate the environmental impacts associated with each component and link constituting the RBS:

Fig. 8.Links results

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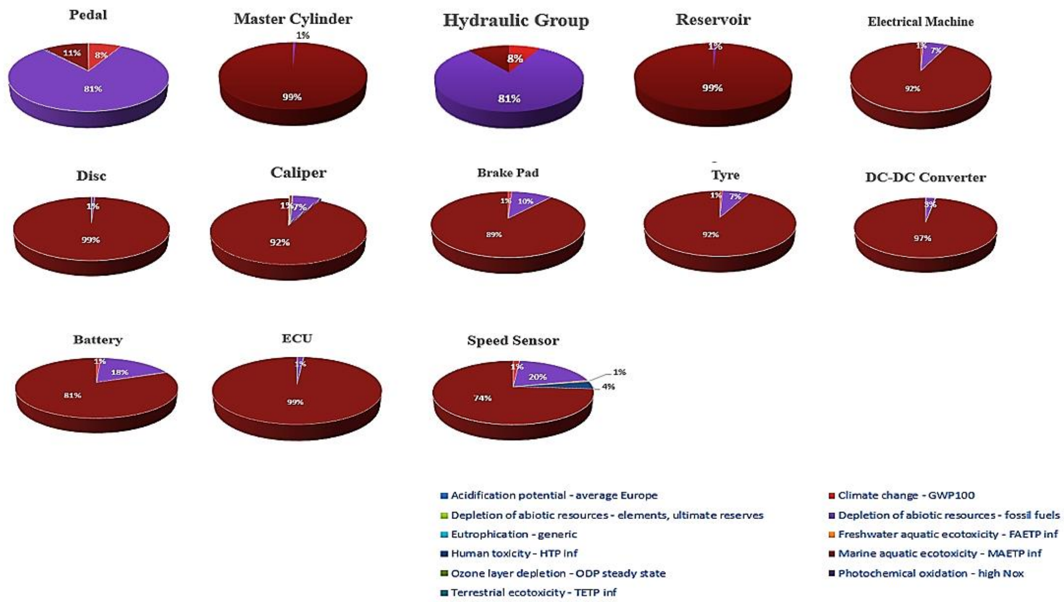
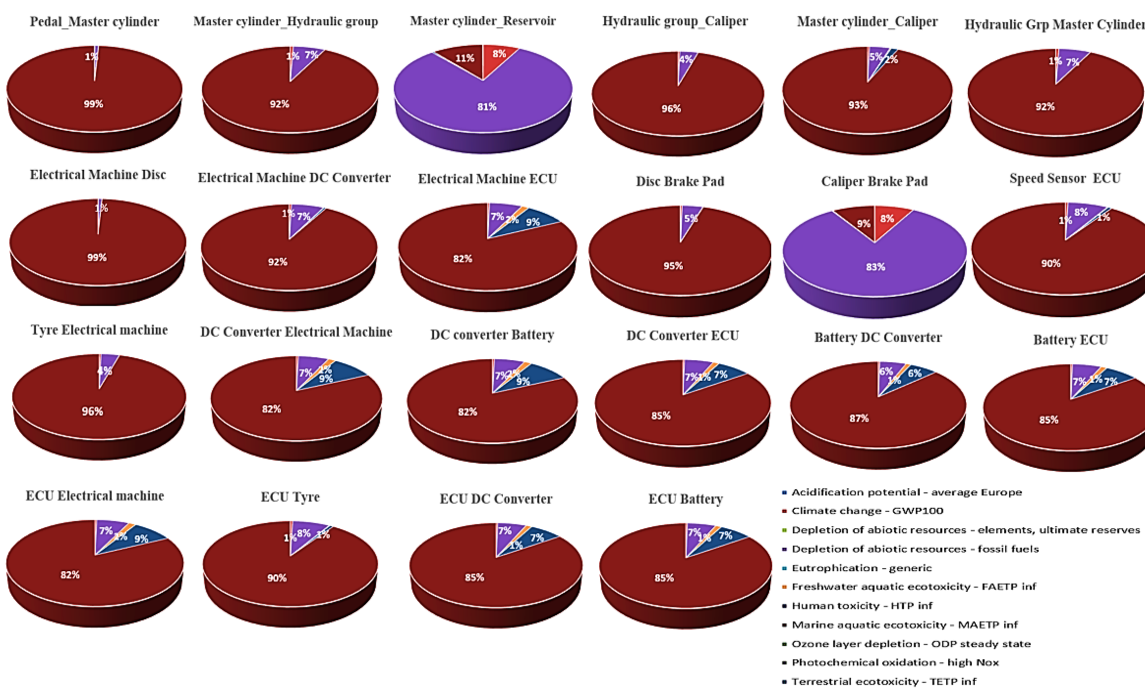


Fig. 9. Components results



The contribution details for each impact category are explained below:

- **Climate change: GWP100**

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The GWP (Global Warming Potential) is a climate metric, developed to describe the future warming associated with a change in the rate of emission of a short-lived climate forcer, such as methane, relative to a pulsed emission of CO2, a long-lived climate forcer. This measure can be used to guide climate action towards the temperature-based climate stabilization goals as set out in the Paris Agreement [18].In our case study, it is resulting from the combustion in production process for different links and components .It's the impact category the most important, could be neglected for pedal, hydraulic group, the link between master cylinder and reservoir, the link between the caliper and the brake pad.

- **Depletion of natural resources:**

The natural resource depletion considers all the resources accessible by extraction and not all the resources present in the entire geosphere (atmosphere, plants, landfills…)[30].CML baseline suggests two kinds of depletion : elements -ultimate reserve , resource's -fossil fuels .This impact arises especially in pedal and the master cylinder components production and master cylinder reservoir and caliper brake pad links (81%).It doesn't exceed 20% for the remaining links and components.

- **Acidification potential -Average Europe:**

Acidification is occurred when acidic substances are present in the air, which can either remain in a gaseous state, dissolve in water ("acid rain"), or attach to solid particles. They thus affect ecosystems (acidification of surface waters, reduction of the fauna and flora living there). This phenomenon also impacts on buildings and human health [31]. The main emissions concerned are SOX, NOX, and to a lesser extent, HCl, NH3, HF. Speed sensor, is the only component concerned by this impact (4%) which could be neglected. Nine links are concerned varying from (7% to 9%) of the total impacts.

- **Ecotoxicity:**

Is the potential for biological, chemical, or physical stressors to affect ecosystems [28]. CML Baseline defines three sorts of ecotoxicity: Marine aquatic ecotoxicity, terrestrial ecotoxicity and, Freshwater aquatic ecotoxicity, this later kind is present in Pedal and Hydraulic group components (8%) and figured in the links between caliper and brake pad in one side and the link between the master cylinder and the reservoir (8%). For the rest of the components and links it could be neglected (1%).

The following impacts are negligible compared to the other impacts already discussed. We will outline their definition:

- **Ozone layer depletion ODP**

The concept of ozone depletion potential (ODP) [19][20][21] has been introduced as a relative measure of a compound's ability to destroy stratospheric ozone. ODP assessment is an inherent part of policy frameworks, including the Montreal Protocol, which outlaws the production of numerous ozone-depleting substances [22].

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- **Eutrophication -generic**

Eutrophication remains one of the most common causes of inland and marine water quality degradation. It generates major disturbances in aquatic ecosystems and has impacts on the associated goods and services, on human health and on the economic activities of the territories where it arises. Eutrophication is the process of enriching water with mineral salts. The main nutrients that are responsible for eutrophication are nitrogen and phosphorous [23].

- **Photochemical oxidation:**

Oxidants, which are formed from the emission of nitrogen oxides and hydrocarbons under the action of sunlight. They are nitric acids, aldehydes, and ozone [29].

4. CONCLUSION AND PERSPECTIVES

Life cycle assessment is a structured tool that can assess the environmental consequences of a company's activity in a very broad way. It is an effective management tool for a company wishing to develop its capacity to systematically manage all environmental aspects related to its product according to "life cycle" thinking. Indeed, the tool enables the production of comprehensive environmental information during the inventory and impact assessment phases, and the identification of significant environmental aspects in view of implementing sustainable improvement actions. During the presented work, a practical study carried out with the Open LCA software enabled us to highlight the main environmental impacts raised during the production of a regenerative braking system. Indeed, Open LCA allows the practitioner to carry out all the steps of modelling, calculation, and results interpretation necessary to carry out an LCA or a simplified LCA, with all the transparency and scientific accuracy required by the methodology and the ISO 14040 and ISO 14044 standards. As a perspective to the presented work, a sustainable conceptual design approach, as an industry-friendly approach, to develop sustainable products and thus fixing the environmental requirements in the early design stages will be suggested based on the life cycle assessment methodology, the requirements classification and then the extraction of the environmentally friendly eligible solution [33].

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