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Procedia CIRP 41 (2016) 626 – 631

www.elsevier.com/locate/procedia

48th CIRP Conference on MANUFACTURING SYSTEMS - CIRP CMS 2015

Life cycle analysis: comparison between different methods and optimization challenges

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Abstract

Sustainability, in terms of energy consumption and the emissions impact on both natural environment and human health constitute a major concern in modern society. In the current study, the environmental footprint of the processes related to the manufacturing of cylinder heads for a diesel and a petrol automotive powertrain is investigated with the use of Life Cycle Assessment (LCA) techniques. These two variants are investigated through different LCA techniques that share the same indicators, aiming at the method's objectivity. In addition, a comparison among different LCA methods has been conducted and the optimization challenges raised by their results have been discussed.

Peer-review under responsibility of the scientific committee of 48th CIRP Conference on MANUFACTURING SYSTEMS - CIRP CMS 2015

Keywords: Life Cycle Assessment; automotive; comparison of LCA methods; sustainability; vehicles manufacturing, optimization

1. Introduction

According to the European Environmental Agency (EEA), the industry sector is responsible for 13% of the total Greenhouse Gas (GHG) emissions in the European region, if considered as an end-user; meaning that both direct combustion emissions and indirect emissions from energy transformation are taken into account [1]. In addition, the industry sector is responsible for 25.3% of the total energy consumption in Europe [2].

In the year 2020, the European growth strategy for the next decade has set that GHG emissions should be reduced by 20% compared to those in 1990. The same goes for the primary energy consumption, which should be decreased from the 1647 Million Tons of Oil Equivalent, of the previous decade, to 1474 during the decade 2010-2020 [3]. Those regulations, along with other restrictions regarding the pollution control, as well as customers pressing for eco-friendlier products, have driven the manufacturing sector, which is a key industrial sector, to develop "greener" strategies, both at production and process level. The first step would be to identify the sources of the environmental impact, caused by a manufacturing process. According to Dornfeld et al. [4], chemical releases and carbon emissions are mainly responsible for the environmental impact of the manufacturing sector. The first impact derives from the production of raw materials and metalworking fluids disposal policies, while the second one is due to the major use of fossil fuels for the generation of electricity that is required for manufacturing processes.

In order for the above environmental impact to be studied and be investigated into for the extraction of possible solutions, an Environmental Assessment (EA) method, namely the Life Cycle Assessment was developed in the early 90's and it is still used by a wide range of companies. According to Chryssolouris et al.[5], LCA is the assessment of the environmental impact of a given product or service throughout its lifespan and it is one of the most well-known analysis methods. The goal of LCA is that the environmental performance of products and services be compared as well as succeed in choosing the least burdensome one. The term 'life cycle' refers to the notion that a fair, holistic assessment requires the assessment of raw material production, manufacture, distribution, use and disposal, including all

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doi:10.1016/j.procir.2015.12.048

intervening transportation steps. Reich-Weiser et al. [6] have classified LCA methodologies into three categories: Process LCA, Input-Output LCA and Hybrid LCA. Process LCA is the one used in most of the case studies, where certain processes included in a product's manufacturing cycle are studied. Along with LCA methodologies, several LCA frameworks have been developed, aiming to standardize the procedures of using LCA. According to ISO 14040:2006 [7], the environmental impact can be separated into three major categories: a) Damage to natural environment, b) Damage to human health and c) Resources Consumption.

Two examples of the practical use of LCA are the studies made by Drakopoulos [8] and Salonitis [9] et al., in which the Environmental Impact of Ship Hull Repair and the Environmental Impact Assessment of Grind-Hardening Process respectively have been performed. In the present study LCA techniques are used in a gate-to-gate approach, for the evaluation of the environmental impact of the machining processes that take part in the production of cylinder heads, for both petrol and diesel engines. Potential improvements of those processes, from an environmental perspective, have also been examined. Furthermore, a comparison between two different LCA methods has been made. The tool used for performing the EA is the OpenLCA, which is a free, professional Life Cycle Assessment software, created by Green Delta in 2006 [10]. The Ecoinvent database has been used as the provider of the processes that connect the system's flows along with the environment ones in order for the calculation of the Inventory to be based on real-world data, leading to a more accurate assessment.

2. Process under Study and System Boundaries

EA has been performed in two stages: a) The Inventory which is the identification and quantification of all the material and energy flows between the environment and the system [11], [12] and b) The Impact Assessment which is the qualitative and/or quantitative characterization and assessment of the environmental threats, as they have been identified in the Inventory [13]. The cylinder heads constitute some of the main parts of an internal combustion engine, since they are located above the cylinder block, which seals its upper part. Their manufacturing process starts with the casting of aluminium alloy to form the initial shape, followed by a series of machining operations, required for the creation of the numerous pockets that enable the passages of the valves, bolts

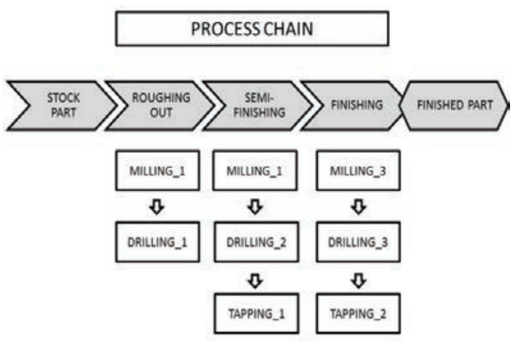


Fig. 1. Sequence of machining processes.

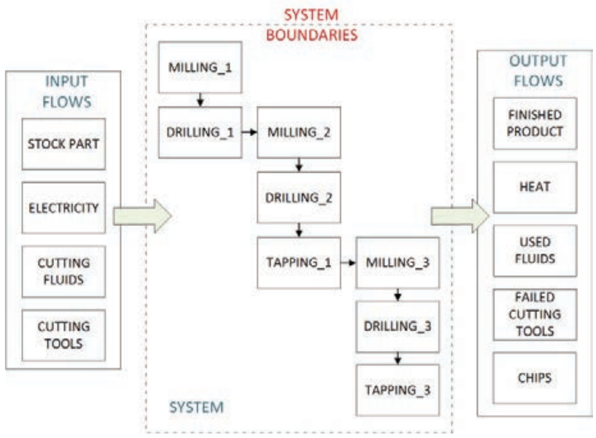


Fig. 2. Cutting processes, input and output flows, system structure and boundaries.

and spark plugs. Of paramount importance are the quality indicators of the surface since it will be in direct contact with the fuel mixture and the combustion gases [14]. The machining phase comprises three stages and eight processes in total, as shown in Fig 1.

In Fig 2. the model that relates the cutting processes to their input and output flows is presented. Even though the input and output flows are qualitatively identical for the whole set of processes, their values differ from one process to another. As noted, this LCA study is performed under a gate-to-gate approach, meaning that the system's boundaries with nature have been set exactly at the point where a part enters or leaves the machining process chain. Thus, operations, such as the casting for the initial shape forming and surface cleaning after machining, have not been taken into account. Moreover, capital goods, namely machine tools and industrial facilities are also excluded from the study. The reason for that is that the life span of this kind of goods is too long to be having a significant impact on a single product's production. A graphic representation of the system's model and its boundaries with nature can be seen in Fig.3. Besides the boundaries between the system and nature, geographical boundaries should be set as well. For that reason, primary production systems (e.g. electricity production) and disposal sites are considered being located in the region, where cylinder heads manufacturing takes place in order for the accuracy of the calculations to be increased. In addition, the stock part and other process input materials, such as cutting tools, are considered being on site and their transportation is not taken into account. This assumption is adopted due to transportation processes being characterized by their extended complexity, thus rendering the collection of sufficient data rather impossible. The ReCiPe Endpoint is used for the assessment of the Ecosystem Quality and Human Health Impact, as it provides a satisfactory number of indicators, belonging to those categories, apart from those in the Resources Consumption. However, a different method, the Cumulative Energy Demand (CED), has been chosen for the assessment of the last category because it provides a greater amount of relevant indicators that lead to a more in-depth approach. The Eco-indicator 99 and IMPACT 2002+ methods are used alternatively for the calculation of the impacts of all three categories.

3. System Assumptions and Inventory

3.1 Machine tool related Data

The processes that have already been described are executed by COMAU Urane 25, a CNC horizontal machining center [15]. The production line studied consists of 30 machining centers in total: 9 in the roughing-out stage, 12 in the semi-finishing stage and 9 in the finishing stage. The data that were used can be seen in Table 1.

Table 1. Machine tool related data.

Category	Value
Processing time	Diesel head: 51 – 54 seconds
	Petrol head: 60 – 66 seconds
Power Consumption - Idle State	9.2 - 10 kW
Power Consumption - Cutting	10.8 - 11.8 kW
Compressed air flow rate	23.5 Nm^3/h
Cutting fluid chemical synthesis	Mineral oil concentration: 5-9%
Cutting tools material	High Speed Steel (HSS)

3.2 Product Related Data

In addition to machine tool related data, the manufacturer has also supplied data of the product are situated in Table 2.

Table 2. Product related data.

Category	Value
Material	Aluminum alloy
Initial weight (before machining)	6.3kg
Final weight (after machining)	5.6 kg

3.3 Assumptions

With reference to the machine tool's operation, the most important assumption made is that every machine's power remains constant throughout the cutting operation. The cutting fluid and compressed air flow rates are also assumed to be constant during cutting and the heat generated during each process, to be equal to the electric power consumed by each machine. Concerning material assumptions, due to the fact that the specific aluminium alloy used by the cylinder heads manufacturer not modelled in the Ecoinvent database, the flow that has been used instead is the average aluminium production mix for alloys. The waste management policy assumed for the waste streams leaving the system (metal chips used cutting fluids and failed cutting tools), is that they follow the disposal route suitable for each of them, as those routes are modelled in the Ecoinvent database, with no recycling policies applied.

3.4 Inventory

Perriman [11] describes the inventory results as "a quantitative description of all material flows and energy across the system's boundary, either into or out of the system itself". In inventory results, the system's input and output flows are analysed in chemical compounds and primary energy resources, named elementary flows and their values are calculated. Data concerning the input and output flows is categorized in two types: Foreground and Background data. Foreground data is that describing the process chain model and refers to the product and production system studied. Background data refers to generic materials, energy, transport and waste management system [16].

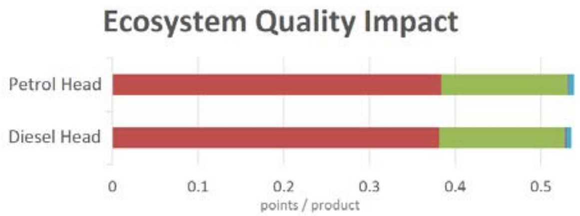
This data is imported to the study from the Ecoinvent database. The system has an output of 1200 elementary flows. A small number of indicative input and output elementary flows, both for diesel and petrol cylinder heads, is being presented in Table 3 and Table 4.

Table 3. Input flows Inventory.

Input Flows	Amount		
	Diesel Head	Petrol Head	Unit
Aluminum, 24% in bauxite, 11% in crude ore	1.4610	1.4610	kg
Natural gas	1.5084	1.5229	m^3
Crude oil	1.5286	1.5352	kg
Kinetic energy in wind	168.4764	177.6826	kJ
Solar energy	1.9257	2.0329	kJ
Zinc, 9.0% in sulfide, Zn 5.3%, Pb, Ag, Cd, In	0.1607	0.1611	kg
Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3%	0.0156	0.0156	kg

Table 4: Output flows Inventory.

Output Flows	Amount		
	Diesel Head	Petrol Head	Unit
Carbon dioxide, biogenic	0.1587	0.1592	kg
Chloride	0.0146	0.0146	kg
TOC, Total Organic Carbon	0.0047	0.0048	kg
DOC, Dissolved Organic Carbon	0.0048	0.0048	kg
Nitrogen oxides	0.0114	0.0115	kg



	Diesel Head	Petrol Head
climate change, ecosystems	0.3814	0.38386
marine ecotoxicity	0.00008	0.00008
natural land transformation	0.14685	0.14716
terrestrial acidification	0.00121	0.00122
terrestrial ecotoxicity	0.00605	0.00607

Fig. 3. Ecosystem Quality impact as measured by ReCiPe.

4. Environmental Assessment: Product Comparison

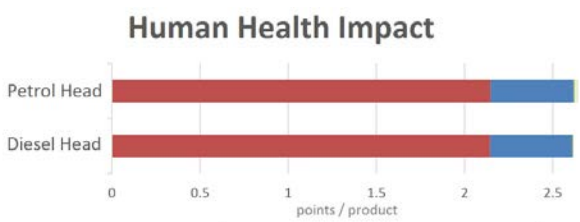
In this stage, the elementary flows entering and leaving the system, after being weighted, are summed up to provide a final score for each impact indicator. The weights applied and the flows taken into account for each impact category are defined by the method used at the time.

The two process chains are compared for the three main types of damage caused to the environment. Firstly, there is a comparison made about the damage to nature and to the human health using the results obtained by the application of the ReCiPe Endpoint method and secondly, the consumption of resources is compared through the results obtained by the application of the CED method.

4.1 Nature and Human Health Damage Assessment

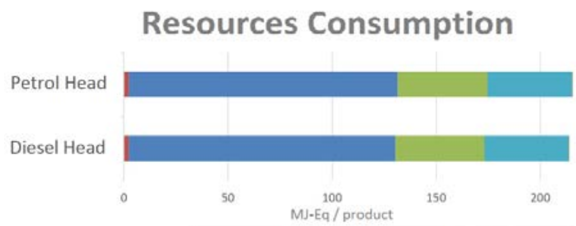
The impact assessment results for both products calculated by the ReCiPe method are presented and compared in the bar charts of Fig.4 and Fig. 5. Damage to nature and to human health is mainly caused by the disposal of used cutting fluids and the operational emissions of primary systems that produce electricity and extract raw materials.

When comparing the impacts of the two process chains, the petrol cylinder head process chain has a slightly greater impact as expected, due to the longer total machining time, while the other parameters remain the same. The petrol cylinder head process chain impact is almost 2.35% greater than the particulate matter formation indicator and only 0.03% greater than the marine ecotoxicity indicator.



	Diesel Head	Petrol Head
human toxicity	2.1436	2.14809
climate change, human health	0.4664	0.4694
particulate matter formation	0.00651	0.00666

Fig. 4. Human Health impact as measured by ReCiPe.



	Diesel Head	Petrol Head
biomass consumption	2.2699	2.285
fossil fuel consumption	127.9594	129.1652
nuclear energy consumption	42.9828	43.3748
solar energy consumption	0.0019	0.002
water resources consumption	40.5905	40.6737
wind energy consumption	0.1685	0.1777

Fig. 5. Resources Consumption impact as measured by CED.

4.2 Natural Resources and Primary Energy Usage Assessment

The impact assessment results for both products were calculated by the Cumulative Energy Demand method and are presented and compared in the bar chart of Fig. 6. When comparing the two process chains, in terms of resources and primary energy requirements, the petrol cylinder head chain has the greatest demands, while the difference percentage between the two chains varies from 0.20% for water resources consumption up to 5.57% for fossil fuels consumption.

4.3 Contribution Assessment

In this section, each process is investigated individually and its contribution, regarding the three major impact categories, is being calculated. The impact contribution analysis is performed using the ReCiPe method due to the fact that it directly provides impact scores for the three categories and as a result, the contribution is easier to be calculated via OpenLCA. In the contribution analysis, the raw material extraction and aluminium waste management processes are not taken into account since they refer to the entire process chain and not to a particular process. The contribution percentages are presented in Fig. 7 and Fig. 8. As far as the diesel cylinder head is concerned, the OP70 has the greatest contribution to the environmental impact in all three categories, while the OP10 has the lowest impact.

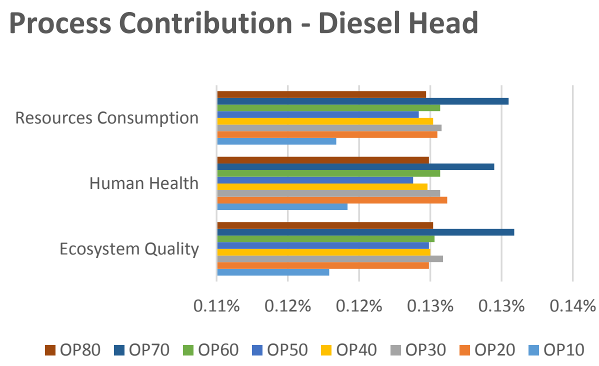


Fig. 6. Process Contribution for Diesel Head.

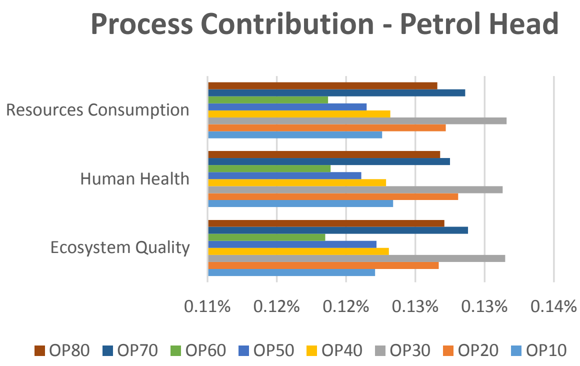


Fig. 7. Process Contribution for Petrol Head.

In the petrol cylinder head process chain, the process with the greatest impact is the OP30 and that with the lowest is the OP60. The quantitative differences of the process contributions between the two chains derives from the different processing time and the use of different cutting fluids, in terms of chemical synthesis, in each machining stage.

5. LCA Methods Comparison

Most of the impact indicators already presented can be measured with the use of other methods, besides those of ReCiPe and CED. In order for the different LCA methods to be compared, the results of the three major impact categories have been calculated by a set of different methods. Only the diesel cylinder head process chain will be used for this comparison. Other methods studied are: Eco-indicator 99 and IMACT 2002+. The above methods have been chosen for the reason that they calculate the impact of the three major categories, along with ReCiPe. Furthermore, the measurement units of the three methods allow a direct comparison. The score of these categories is calculated by summing up the scores of the indicators, belonging to each category.

Before proceeding with the comparison of the three methods, the method dependency on the relative impact of the two products has to be investigated. The greater environmental impact of the petrol process chain regardless of the method used can be clearly seen (Table 5).

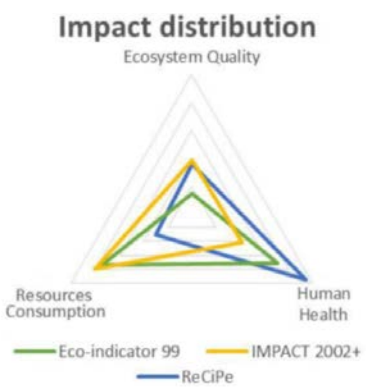


Fig. 8. Impact scores distribution.

5.1 Impact Results Distribution

A first approach to the methods' comparison is performed by investigating the distribution of the impact scores of each method, as it is shown in Fig. 9. In analysing those graphs, the Eco-indicator 99 has an almost equal distribution to the Human Health and Resources Consumption categories, while having a negative value for the Ecosystem Quality category. On the other hand, ReCiPe and IMPACT 2002+ have a similar distribution to the Ecosystem Quality category.
The difference between the two methods is that the ReCiPe results in a much larger value for the Human Health category than the Resources Consumption category does, while the IMPACT 2002+ has exactly the opposite scores distribution to the two impact categories.

Table 5. Impact results for both products using three different methods.

Impact Category	Method	Diesel Head	Petrol Head
Ecosystem Quality	ReCiPe	0.5392	0.5420
	Eco-indicator 99	-0.0262	-0.0261
	IMPACT 2002+	0.0003	0.0004
Human Health	ReCiPe	2.6172	2.6249
	Eco-indicator 99	0.2474	0.2485
	IMPACT 2002+	0.0004	0.0004
Resources Consumption	ReCiPe	0.3567	0.3601
	Eco-indicator 99	0.2648	0.2674
	IMPACT 2002+	0.0011	0.0012

5.2 Impact Results Comparison

In this section, a comparison between the methods is made using the results from the calculations of all three common impact categories (Fig. 9). The analysis of the charts shows that in all three impact categories, ReCiPe, followed by Eco-indicator 99, is the method that provides the greatest score values. Finally, in the Ecosystem Quality, the category Eco-indicator 99 results in a negative score, meaning that any environmental threats have been avoided, in contrast to the ReCiPe that results in a positive value. The scores calculated by the IMPACT 2002+ method are much lower than those of the other methods by two to four orders of magnitude. As a result, the values of each method cannot be directly compared with the other two.

6. Discussion and Conclusions

A comparative LCA approach of the environmental impact of the manufacturing of cylinder heads for diesel and petrol engines has been presented. In addition, a comparison between impact assessment methods has been conducted.

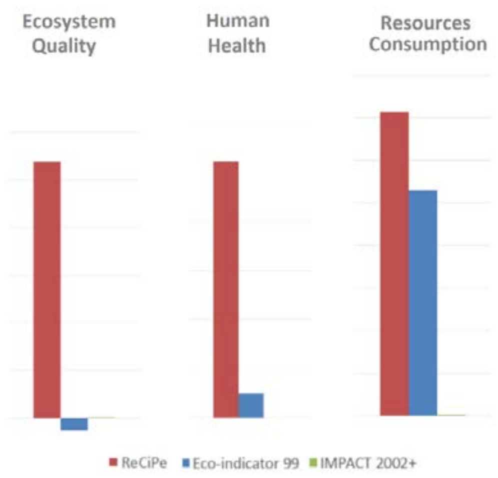


Fig. 9. Ecosystem Quality, Human Health and Resources Consumption results comparison.

The petrol cylinder head process chain has a slightly greater value for all the environmental impact indicators studied. The indicator with the greatest difference between the two products is the "Fossil fuels consumption", which is 5.57% higher for the petrol head process chain. The smallest difference is located in the marine ecotoxicity indicator, where the petrol head has a 0.03% greater impact. The different impact of the two process chains can be attributed to the shorter total processing time of the diesel head compared to that of the petrol head.

As far as the method comparison is concerned, direct comparison between the values of the indicators of each method has to be avoided, since the scores used by some methods lead to results with differences of 2 to 4 orders of magnitude. Most of the times, the same product will be calculated as the most harmful one, regardless of the method used each time. However, it is possible for a different product to be considered as the most harmful by two different methods. This can be attributed to the fact that each method using different weight coefficients for each impact score and it takes into account partially different elementary flows Thus, the use of more than one method is recommended, so as for a more global view of the product system to be obtained. The CED method, which has been used in the Resources Comparison category uses MJ-Eq, whereas the ReCipe, which has been used in the Ecosystem Quality and Human Health categories, uses assessment points. However, MJ-Eq is a universally used unit and can be used in general for comparisons, in contrast to the assessment points that do not even allow comparisons between the results of another LCA method.

Notable is also the fact that the impact of different output flows may vary between the same systems, situated in different places. Specifically, the use of different resources, according to the local availability, may render a product more harmful, depending on the manufacturing location. Moreover, the most harmful process of different products, even among very close ones, may differ. The combination of both observations can contribute to the supply chain management optimization by assisting with the selection of the place, where a manufacturing system will be placed, according to the processes included in it for the minimization of the environmental harm.

Finally, in order for a direct comparison of the different LCA methods' results to be possible, weight factors can be calculated for pairs of different methods.

Acknowledgements

The work reported in this paper was partially supported by CEC / FP7 NMP-ICT Programme, "The Foundation for the Smart Factory of the Future-FoFdation", (FP7-2010-NMP-ICT-FoF- 260137)

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