Comparative LCA of Automotive Gear Hobbing Processes with Flood Lubrication and MQL

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Abstract

The Life Cycle Inventory (LCI) data of a gear hobbing was obtained by means of the methodology Unit Process Life Cycle Inventory (UPLCI), in order to conduct a comparative Life Cycle Assessment (LCA) between hobbing assisted by Flood Lubrication (FL) and Minimum Quantity Lubrication (MQL). The results of the LCIA pointed out 4 among 11 normalized environmental impact categories totalized more than 80% of the accumulated impacts: fossil depletion (43%), climate changes (19%), terrestrial acidification (11%) and freshwater consumption (8%). The identified hotspot in the case study was the input flow of raw material for the system “Hobbing Machine”, which was linked to more than 75% of the total amount of normalized potential environmental impacts. Once, changes on raw material depends on the gear design, the research focused on the environmental aspects of energy and cutting fluid consumption, which depends directly on the hobbing process parameters. The introduction of MQL provided reduction of 70.77% on the total amount of normalized potential environmental impacts, while the strategies to reduce electric energy consumption by the machine tool accounted only for 3.74%. The consumption of energy and cutting fluids are the main environmental aspects of the gear hobbing process itself, since they are directly associated to the majority of potential environmental impacts derived from that machining operation. Nevertheless, when raw material flow is taken into account in the LCA, it turns into the process hotspot, due to high energy demanded in the steel-making process, forging and turning operations to shape the semi-finished gear.

1 Introduction

The industrial segment consumes near to 30% of total amount of energy available globally within the end users sector [1]. Wegener et al. [2] and Liu et al. [3] highlight that a considerable part of this energy consumption is due to machining processes in the manufacturing industry, which can trigger environmental impacts such as fossil depletion and climate changes [4]. Moreover, the intense use of cutting fluids in machining operations can also lead to the occurrence of other environmental impacts such as human toxicity, that may result in occupational diseases, from skin irritations to cancers [5].

Therefore, the study of the diverse environmental aspects associated to machining operations figure as a relevant activity inserted in the lifecycle management of industrial environments. In this sense, the LCA has become an acknowledged tool for the evaluation of environmental impacts, in connection to the complete life cycle of products, processes and economic activities [6].

In regard to the manufacturing phase within the LCA of a product system, Silva et al. [7] identified, among researches in Green Manufacturing, some proposals focused on: the energy consumption analysis, the practice of LCA per se and the machining processes design. Campitelli et al. [8] explain that the design of a machining process can employ the technique known as Minimum Quantity Lubrication (MQL), which is associated to expressively lower environmental impacts when compared to results obtained by the use of conventional Flood Lubrication (FL).

Although the LCA find direct application on the industrial machining, Arena et al. [9] claim its practice is difficulty, once it requires the inventory data of each component, that composes the assembled final product, and, the systematic data collection and interpretation of diverse energy and material flows of all relevant activities throughout the entire product lifecycle. The authors also highlight, as obstacles for the realization of LCA, the lack of LCI datasets, which may lead to definition of uncomplete system boundaries, missing some processes, and, as consequence, resulting in underestimated environmental impacts.

Suh et al. [10] clarify the LCI database are valuable resources for the conduction of LCA, once they help on reducing the time and resources invested in analysis and evaluation, since the available datasets can be employed initially to detect hotspots, before the practitioner decides to work on data collection. In addition to this, the LCI databases help on increasing the comparability among LCA.

There is a scarcity of LCI about machining processes, once the LCA studies are more frequent in products than manufacturing processes [7]. Brundage et al. [11] affirm the LCA methods rely on LCI data containing impact estimates of manufacturing processes. Thus, the accuracy of LCI data is critical for quality assessments, however available datasets are often insufficient to cover the variety of existing machining processes and are often only a coarse estimate of actual impacts. Gamage et al. [12] noticed the lack of LCI datasets is more evident for non-conventional machining processes, such as: electrochemical, electroerosion, laser or electrons beam, water jet and other hybrid processes.

The adaptation of existing LCI datasets from one global region to another could be a solution for the data scarcity, however Henriksen, Astrup e Damgaard [13] warn that data non-representativeness can take place when datasets containing a specific technology are assigned to replace a mix of technologies, or, the average data from a region are employed as replacement to process data in a specific location.

In Brazil, the development of LCI is more recent when compared to European and North-American initiatives. The national database of life cycle inventories – SICV Brazil was firstly published in 2016 [14], and, today, its collection includes 22 published process datasets [15].

In this way, researches on life cycle inventories of manufacturing processes add value to the life cycle studies, as they contribute to increase the accuracy of the LCA, which constitutes guidance to drive projects and initiatives to foster sustainability in public and private spheres. In particular, to the Brazilian context, the LCI researches contribute to the creation of genuine national datasets, which capture actual aspects of local industrial and economic activity, and, encourage additional LCA studies and applications. The datasets produced by the present research may compose the LCI database SICV Brasil, in conformity to the Qualidata Guidelines [16].

The focus of present research is to conduct a comparative LCA between automotive gear hobbing processes assisted by FL and MQL, in order to evaluate the potential environmental impacts derived from those 2 processes configurations. To provide foundation to the mentioned LCA, a literature review about LCI methodologies was carried out. As part of the LCA, 3 different process setups for the gear hobbing were proposed to decrease energy and cutting fluid consumption, and, the corresponding effects over the potential environmental impacts.

In Sect. 2, the literature review approaches the core topics: LCA of machining processes employing MQL, and, specifically, LCA of gear hobbing process; the methodology UPLCI and the interplay with LCA practice and its guideline ISO 14044:2009 [17]. Section 3 presents the methods and resources employed to carry out the case study. In Sect. 4, the results of the LCA and the conducted sensitivity analysis are provided and discussed. Finally, Sect. 5 concludes the paper comparing the case study findings to the previous published researches on LCA of gear hobbing, and, suggesting future research directions.

2 Literature Review

2.1 LCA of Machining Processes

The use of LCA to investigate the potential environmental impacts of machining processes in the industry, worldwide, has achieved different deployments, such as: identification of machining process hotspots; machining process parameters optimization aiming at lower environmental burden; comparison between conventional machining processes and additive technologies; integration of LCA into the product and process development phases, as presented by Sharma et al. [18], Campitelli et al. [8], Awad et al. [19], Kamps et al. [20], Filleti et al. [21] and other researchers.

One huge source of energy consumption in the machining process are the machine tools. According to Stehlík [22], the energy output costs for operating ten years the same machine tool is 100 times higher than their own acquisition cost. Pusavec et al. [23] enhances the key factor to increase the environmental performance of the industrial machining processes is reducing the energy consumption, once 10% is employed to air compression systems, 40% on machine electric drives, and, 40% to heating and lighting.

2.1.1 LCA of Machining Processes with MQL

One important environmental aspect of the machining processes is the application of cutting fluids to control heat generation during the material remotion by the cutting tools, in order to keep work piece quality requirements, while optimizing the cutting tool lifetime [24, 25]. However, the use of cutting fluids present some side effects, such as the dispersion of hazardous substances like biocides and chemical additives to fight the growing of fungi and bacteria into the cutting fluids and control oxidation of machine parts, work pieces and tools. Shashidhara and Jayaram [26] and Shokrani et al. [27] stated cutting fluids dispersed as liquid, and, into the air, as aerosol, can cause diseases like asthmas, lung, esophagus, colon cancers, and diverse occupational infections in the production environments.

One promising technology used to fight the environmental impacts of cutting fluids is the MQL. It involves the delivery of small quantities of cutting fluids, between 10 to 100 ml per hour, mixed to compressed air, as aerosol, directly into the machining cutting zone [28]. The Fig. 1 shows the lubrification mechanism by means of a milling operation.

Although, MQL employs mineral oils, its consumption is reduced drastically, by a factor of until 10,000 times over original use, in flood lubrification technics [29, 28].

Grzesik [30] compared metal machining performance for flood lubrication (FL), near-dry machining (NDM) and MQL assistance technologies, ordering the aspects: lubrication and refrigeration effects, chips transportation and recyclability, investments in technology, operational and disposal costs, health aspects, protection against corrosion and cutting fluid waste (Fig. 2). In most of analyzed aspects NDM and MQL showed higher performance, although NDM use is prevent in some situations due accelerated cutting tool wear.

Campitelli et al. [8] concluded MQL was widely favorable than FL for drilling and milling processes in aluminium, steel and iron alloys, once MQL provided significant reduction of potential environmental impacts over FL: climate changes (44%), abiotic resource depletion (31,5%) and land use (70.3%), considering 70% of the impacts connected to the energy consumption and 27% to cutting fluids.

2.1.2 LCA of Gear Hobbing Processes

The machining technology most employed to manufacture gears is the gear hobbing process, especially for spur and helical gears, because it provides lower production costs and higher dimensional accuracy than other methods [31].

Tapoglou et al. [32] stated the gear hobbing is characterized by a complex geometry in the interface between the hob and the workpiece, with different hob cutting edges removing material simultaneously, causing different chip forming. Brecher et al. [33] pointed out that gear hobbing process design depends on empirical parameters such as metal chips color, shape, and width, which serve as input data to estimate cutting efforts developed during the machining.

Xiao et al. [34] proposed an empirical formula to calculate the cutting efforts by hobbing. It encompassed 12 parameters such as empirical coefficients obtained by means of orthogonal experiments, and, geometrical tool and gear features, such as module, teeth number, and process parameters such as hob angular speed, feed rate.

Stachurski and Kruszyński [35] explained that gear hobbing assisted by MQL has not been studied in depth yet. They carried out some experiments varying the cutting speed with high-speed steel hob cutters and concluded cutting speed up to 54 m/min. associated with MQL ensure suitable lubrification in the cutting zone, and, therefore prevent the progressive wear of hob cutter.

In 2019, 92 Million vehicles were produced globally [36]. It means, more than a Billion of gears were manufactured only for application in the automotive segment. Within this context, comprehension of potential environmental impacts derived from gear hobbing process can be seen as a relevant research theme.

The search for research work by means of combined terms “LCA”, “gear hobbing” or “gear milling” or “gear manufacturing”, resulted into selection of only 3 articles published in 2010, 2018 and 2019, in the database “Web of Science”.

Fratila [37] compared the gear hobbing of gears manufactured from steel alloy DIN 16MnCr5 assisted by conventional FL and MQL. The process configuration with MQL consumed 9% less energy than the one set with FL, due to constant liquid cutting fluid pumping into the cutting zone. In regard to environmental impacts, the method Eco-indicator99 revealed hobbing process with MQL provided 8% less potential impacts than hobbing with FL.

Zeng et al. [38] proposed a LCA-based methodology to support decisions in designing machine tools under the perspective of Ecodesign, aiming at the reduction of energy output throughout the use phase of such equipments, once they consume 75% of energy demanded by the industrial manufacture, which, in turn, employs 33% of the annual global energy offer and 20% of global CO_2 emissions. The case study performed with a gear hobbing machine tool showed the resulting carbon footprint, in Tons of CO_2 equivalent, got contribution of the environmental aspects: energy consumption in the machine tool use phase (84%); production and tools (10%); raw material obtainment (6%); machine tool manufacture (3%); transport (1%) e recycling phase (6%), although such percentages may range according to the constructive technology and type of machine tool.

Jiang et al. [39] compared the environmental performance of small gears weighting 10 grams, produced by CNC- hobbing, in steel DIN 42CrMo4, and, the additive manufacture technology named Laser Engineered Net Shaping (LENS), where the part in formed by multiple successive layers of steel alloy obtained by the fusion of metallic powder melted by high power laser beam. The conclusion is that LENS process achieved less potential environmental impacts due to lower consumption of energy and production consumables, although quality and process scalability were not monitored in the course of the case study.

2.2 The Methodology Unit Process Lifecycle Inventory (UPLCI)

Unit process life cycle inventory (UPLCI) is a modeling approach that enables users to estimate the energy use and material flow of a unit process, allowing the reuse of such models in a wide range of machines, products, and different materials [40, 41, 42, 43].

The methodology UPLCI was introduced by Kellens et al. [44, 45] aiming at the offer of procedures to enable the generation of robust and complete unit process inventory data, in order to contribute on the identification of potential environmental improvements for the analyzed processes. The UPLCI was designed to provide the practitioner one framework to collect process inventory data, both, by equipment subunit levels and by its use modes [21].

Kellens et al. [44] developed 2 approaches for the application of the UPLCI: the “Screening” approach is based on mathematical and computational engineering, and, the “In-depth” approach employs real-time measurements of the manufacturing process.

The “screening” does not include data collection in the shop floor and provides an initial description of the process inventories. On the other hand, the “In-depth” approach is time-consuming, since process primary data collection is mandatory, nevertheless it supplies more precise and complete inventory data, helping more at the detection of process environmental hotspots [44].

The application of methodology UPLCI is guided through 8 steps, mainly, covering: process classification according to DIN 8580:2003 taxonomy [46]; generation and collection of inventory data based on engineering calculation, industrial process measurements or combination of both; LCI dataset peer-reviewing and publication; proposition of actions to improve process environmental performance and guideline of best practices.

As a core step in the methodology UPLCI, the inventory data collection, Kellens et al. [44] explain the goal and study scope must be clearly defined and consistent with the intended unit process. Therefore, some activities must take place:

i. investigate machine tool architecture and the most influential process parameters;
ii. identify the sub-processes, machine tool subsystems and production modes to be monitored throughout the study;
iii. define the system boundaries; its functional unit and reference flow.

2.2.1 System Boundaries, Functional Unit and Reference Flow

The definition of system boundary should declare the studied process and its sub-processes, process input and outputs, justifying the excluded ones provided their low relevance to the study. Linke et al. [41] claims that machine operation should not take into account the influence of external elements such as material handling and feeding into the system boundary.

Kellens et al. [44] state, that, in UPLCI studies, the system boundaries are set to encompass only the operating phase of the unit process, excluding the manufacture or disposal of the corresponding machine tool, as shown in Fig. 3. Moreover, all inputs and outputs from Technosphere and Ecosphere must be listed (Fig. 3).

The next step is picking the process parameters, which are relevant to process performance, in reference to a quantitative and qualitative measurable functional unit. Thus, input and output flows in / from system boundary always refer to the functional unit [44].

The description of the functional unit specifies a performance indicator to functional output flows in the analyzed product system, serving to establish the reference flow, that measures the quantity of demanded product to fulfill its previously assigned function [47].

Kellens et al. [44] propose to use a generally applicable reference flow of 1 second of processing time for a specified load level of a unit manufacturing process for a specified material, based on a working scheme of 2,000 hours per year.

2.2.2 Inventory Analysis in Manufacturing Processes

The LCI phase, according to the ISO 14040:2009 [47], consists of collecting data regarding all the inputs and outputs to/ from the product system related to environmental impact categories of interest [44]. The "In-Depth" approach determines the conduction of 5 studies to measure and analyze the materials and energy consumption synchronized to real-time manufacture operation.

Kellens et al. [44] explain the time studies are developed to spot the different use modes of machine tool, the respective process parameters, counting the time for each use mode and active machine subunits. Directly connected to time study, the power study maps the electric energy consumption by each machine tool processing unit, in each use mode. The energy consumption is calculated by the power consumed and the duration of each machine use mode, for both machine tool and the corresponding active subunit.

For the consumable study, Kellens et al. [44] indicate the measurement of consumed compressed air, lubricants, water, tools, and other material employed in each processing unit and production mode, in parallel to the time and power studies. The generated amount of waste must also be included as consumable in the study, once its recycling, combustion or landfilling impacts need to be taken into account when the UPLCI data are used in the modelling of a product LCI. Where relevant, gaseous, liquid and solid emissions measurements need to be performed for each production mode, and, expressed in volume units or in weight per volume.

2.3 LCIA and LCA Interpretation in Manufacturing Processes

Although the LCIA does not compose the methodology UPLCI, it is essential to interpret the LCA results in reference to the questions posed in the definition of LCA goals [48]. The main goal of the LCIA is to classify and to bring forward the relevance of potential environmental impact of each inventoried flow in the LCI phase [47].

There are dozens of LCIA methods available in the literature, and the application of their proposed environmental impact categories depends on studied process. Firmino [49] points out the most used LCIA Methods in manufacture processes are: ReCiPe [50]; IMPACT 2002+ [51]; Eco-Indicator 99 [52]; e CML2001 [53], as shown in the Table 1.

Table 1
– LCIA methods employed on LCA of manufacturing processes (Source: Firmino, [49])

LCIA method	Method Type	% of Use
ReCiPe	Midpoint + Endpoint	60
IMPACT 2002+	Midpoint	40
Eco-Indicator 99	Endpoint	10
CML2001	Midpoint	10
Others	-	10

EC/JRC/IES [54] highlight 2 purposes for the LCA results interpretation - the last phase of an LCA:

- it provides hints for the improvements of LCI model based on the scope and goals of the LCA, which were set initially in the study;
- it serves to underpin technical and management decisions and recommendation referring to studied product or process.

According to the ISO 14044:2009 [17], the LCA interpretation phase comprises: the identification of hotspots derived from the results obtained in the LCI and LCIA; evaluation of LCA in regard to its completeness, sensibility, and consistency; the presentation of the study findings, limitations, and recommendations.

The use of UPLCI methodology leads to recording the LCI of manufacturing processes in such way that allow comparisons between machining processes, even if they present distinct characteristics.

3 Methods

The methodology UPLCI was used to develop a case study about the hobbing operation of automotive gear teeth. Afterwards, the LCI data was entered into a LCA model considering 4 scenarios for this hobbing operation.

3.1 Case Study

The case study was conducted in the plant of one auto parts manufacturer located in the state of São Paulo, Brazil. The gears and other components are used in the assembly of commercial vehicle transmissions systems for the South-American market.

The hobbing operation was assisted either by FL or the MQL. The materials, procedures, work premises and techniques employed at the study case are described in the following subsections.

3.2 Materials

The machine tool used in the study is a hobbing machine, model S300, year 2011, manufactured by the company Samputensili, operating on three-phase voltage of 380 VAC, 60 Hertz, equipped with a Siemens Sinumerik numeric control. For the study case, the premises below were observed: a) machine tool set up with a multiple thread involute hob (Fig. 4B); b) cutting assisted by conventional FL, and, MQL supply, in distinct time periods; c) gear teeth module 4.5 mm, 32 teeth and 14 kg of mass, typical dimensions of gears for heavy duty commercial vehicles (Fig. 4C); d) annual gear production of 80,000 units.

The machine tool has three linear axes (X, Y, Z), three rotating axes (A, B, C) and one robot arm for positioning the workpieces (Q) according the Schema shown in the Fig. 4A.

Over the machining time, the hobbing cutter rotates about the axis B while the hob head moves in an axial direction along the gear axis (Z axis). Simultaneously, the work gear rotates about the axis C. At the end of operation, the robot arm holds the machined gear, turns 180°, and, positions a new blanked work gear onto the worktable to start a new machining cycle.

The machine tool operates in six distinct states, according to the ISO 14955-1:2017 [56], from the full machine systems activation level to the state characterized by absence of power supply from the industrial electrical grid:

a. state “Processing”: mains power switch (ON), machine control (ON), peripheral units (ON), machine processing unit (ON), material removal from work gear ongoing, machine motion unit (ON) and axes moving;
b. state “Warm Up”: mains power switch (ON), machine control (ON), peripheral units (ON), machine processing unit (ON), no material removal, machine motion unit (ON) and axes moving;
c. state “Ready for Processing”: mains power switch (ON), machine control (ON), peripheral units (ON), machine processing unit ON HOLD, machine motion unit (ON HOLD);
d. state Extended Standby”: mains power switch (ON), machine control (ON), peripheral units (ON), machine processing unit (OFF), machine motion unit (OFF);
e. State “Standby”: mains power switch (ON), machine control (ON), peripheral units (OFF), machine processing unit (OFF), machine motion unit (OFF);
f. State OFF: mains power switch (OFF).

Within one hobbing cycle, the “Extended Standby” state takes place right after the material removal phase and lasts until new blanked work gear is positioned onto the worktable. On the other hand, the state “Standby” is activated for longer machine downtimes, such as meal breaks, shift changes and weekends.

Over one entire hobbing cycle, the machine tool switches among the states “Processing”, “Warm Up”, Ready for Processing” and “Extended Standby”, which actuate over the hobbing machine subunits:

- Primary system (lighting, control unit, sensors)
- Hydraulic unit;

- Hob spindle;
- Worktable spindle;
- Axial, radial and vertical feed drives;
- Rotating drives;
- Exhausting system;
- Cooling system;
- Compressed air system or flood lubrication pump;
- Chips extraction conveyor.

The Fig. 5 presents a correspondence between machine tool operating states and the activation states of its subunits in order to support the data interpretation and identification of energy consumption sources in the LCI.

3.3 Methods

3.3.1 Functional Unit, Reference Flow and System Boundaries

In accordance to the methodology UPLCI [44], the functional unit was expressed as the removed material volume during the hobbing operation. The removed volume within one second defines the functional unit as: 0.67 cm^3 of steel alloy 20MnCr5, from the blanked work gear.

Likewise, as recommended by Kellens et al. [44], the reference flow is the same as the functional unit, expressed within one second of operation, including the machine tools operating modes: full load, partial load and standby.

The scheme outlined in Fig. 6 shows the system boundaries, including its inputs from Technosphere, outputs to Technosphere, emissions to the Ecosphere, and, the hobbing machine operation states and its subunits.

3.3.2 Premises about the LCI

The data collection phase was guided by the “In Depth” approach of the methodology UPLCI. Kellens et al. [44] enhanced this research approach provides higher data precision and completeness, which support the identification of potential improvements in the corresponding manufacturing process, from the raised environmental hotspots obtained from the LCA. The ‘In Depth” approach is also useful to aggregate data for the development of future inventories and LCI datasets of manufacturing processes.

After establishing the system boundaries, it was determined the Background Data would be taken from the database of the software GaBi, and, the Foreground Data would be collected directly into the production site, according to the following stages:

- measurement of electric energy consumption at each machine tool operating state throughout a complete hobbing cycle of one gear;
- indirect measurement of the consumables: steel alloy from the blanked work gear, cutting fluid, hob and compressed air, at each machine tool operating state throughout consecutive hobbing cycles, along 1.000 hours;
- indirect measurement of the recyclable chips from the material removed from the blanked work gear, at each machine tool operating state throughout consecutive hobbing cycles;
- compilation of collected data to calculate the total amount of inputs and outputs of the product system, and, the derived balances of mass and energy (Fig. 6).

Time study

The complete hobbing cycles was timed and distinguished among the different machine tool operating states. Each cycle started when the hob head moved in Y-direction towards a new blanked work gear fixed onto the machine worktable. until the moment a new work gear is fixed onto the worktable by the robot arm and machine enters the state “Ready for Processing”, indicating a new cycle. The hobbing cycle was repeated 5 times consecutively to detect any variation among the different operating states of the machine tool.

Power study

The electric energy consumption compilation took place in indirect way, by means of the electrical power measurement in the machine tool, by means of the Three-Phase Power Quality and Energy Analyzer - FLUKE 435. This device was installed at the machine tool electric panel for the real-time measurement of consumed electric current and tension, in each of the three phases, as well, the active power.

The measurement data was stored in the intern memory of the device, and, subsequently transferred to an electronic spread sheet for the handling and data arrangement for the LCI.

The power study was repeated five times for the current production setup, and, additional seven times, in different combination between hobbing cutter feed rate and rotational speed of the spindle. To ensure feasible production conditions, the combination of feed rate and speed were limited by technical admissible parameters of the hobbing process, such as width and color of metal chips and dimensional accuracy of machined gears.

Consumables study

Besides the electric energy consumption, the listed consumables employed on the hobbing operation were monitored by an indirect counting method: (i) raw material, as blanked work gears; (ii) cutting fluid; (iii) hobbing cutter; and (iv) compressed air. In regard to the generated wastes, the study encompassed: (v) metal chips; (vi) contaminated cutting fluid; and, (vii) worn-out hobbing cutter.

The consumption measurement of raw material and solid waste – the metal chips, was carried out by controlling the gear mass, before and after the hobbing operation. Thus, the difference between values determined the raw material mass converted into metal chips.

The volume of metal chips resulted from the metal chips mass measured previously, multiplied by 7,895 Kg / m^3, which corresponds to the specific volume of steel alloy 20MnCr5. The direct measurement of metal chips was discarded due to the lack of precision, once there is not ensured the full content of chips will be transported by the extract conveyor to the outside collector, because the chips are thrown apart under high speed during the machining, those particles may fall down on the machine tool bed instead of the conveyor.

The consumption of cutting fluid was determined by means of compilation of 1.000 hours of production data, that were registered by the factory maintenance field team. The cutting fluid reservoir was part of the MQL system, which was installed onto the back panel of the machine tool. Every maintenance event that resulted into addition of cutting fluid into the MQL system reservoir was taken into account to calculate the fluid consumption per produced gear. Therefore, the cutting fluid consumption was the quotient result between the cutting fluid consumption within 1.000 hours of production and the quantity of gears produced within this period.

Nevertheless, the machine tool operated many years with the conventional FL before the introduction of the MQL. Thus, the consumption of cutting fluid per gear was also calculated based on the historical data of maintenance department for more than 5.000 hours of this machine tool operation.

The resulting volume of contaminated cutting fluid after the hobbing operation was determined by the difference in weight of a mass of chips, in wet and dry conditions. One sample of 1,030 grams of metal chips, corresponding to the amount of material removed from one blanked work gear, was extracted by the machine tool conveyor, and weighted by a scale with resolution equal 0.1 grams. Once the metal chips were contaminated with cutting fluid, the sample was dried in an oven, to cause the evaporation of the liquid adhered to the chips, and, weighted again. The difference between the weighted values was taken as the net amount of contaminated cutting fluid, and, it was used to both, the LCA model of gear hobbing assisted by FL and MQL.

Finally, the consumption of the hobbing cutters per produced gear was calculated by the quotient between one tool and the number of gears this tool was able to machine, before it was sent to reshaping services.

Emissions study

The machine tool is equipped with electrostatic filter to absorb dust, fumes and oil mists, which are formed due to excessive generation of heat in the cutting zone, chemical characteristics of the cutting fluid and its pumping pressure onto the cutting zone. The machine tool working space is completely confined, meaning the exhausted air from the hobbing machine is integrally filtered and delivered to the manufacturing plant environment, at atmospheric pressure and below 5 mg/m^3, that is the threshold for emission of dust, fumes and oil mists in accordance to the Brazilian Regulatory Standard 15 [57].

The machine tool is also equipped with an external refrigeration unit, that operates with the fluid R134A, within the temperature range of 15°C and 45°C, and, delivering 7.900 W of power for cooling the machine hydraulic system circulatory oil. During the conduction of the case study, the dissipated air temperature reached 38ºC, measured at 50 cm away from the refrigeration unit. This result indicated the equipment operation near to the machine tool was not classified as unhealthy working station according to the Brazilian Regulatory Standard 15 [57].

3.3.3 Premises about the LCIA

Basing on the study case data, composed by the data collected directly at the machine tool and historical records of factory field maintenance team, the LCIA was carried in the software GaBi, version 9.2.1.68 - Education Database 2020, which is suitable for academic researches.

ReCiPe 2016 v1.1 Midpoint (H) [58] was the method picked to the evaluation of environmental impacts, once that method is the most adopted to conduct the LCIA of manufacturing processes, as presented in Sect. 2.2.2. Among 15 impact categories listed in the mentioned method, Firmino [49] enhanced 11 categories, which are preferred to analysis of machining processes and were used in this research work:

i. Climate Change, default, excl biogenic carbon;
ii. Fine Particulate Matter;
iii. Freshwater Consumption;
iv. Freshwater Eutrophication;
v. Metal Depletion;
vi. Terrestrial Acidification;
vii. Terrestrial Ecotoxicity;
viii. Fossil Depletion;
ix. Freshwater Ecotoxicity;
x. Human Toxicity, cancer;
xi. Human Toxicity, non-cancer;

4. Results And Discussion

4.1 LCI

The data collected during the conduction of case study are presented in this section, in reference to one complete hobbing cycle of one gear, and, based on the reference flow set in the Sect. 3.3.1. The gathered inventories were: electric energy output of the machine tool operating in different states, generated consumables, and waste.

4.1.1 Time Study Data

The Fig. 7 presents, in a chronological sequence, the operating states assumed by the machine tool and their corresponding duration over one complete hobbing cycle of one gear, as well the total time assumed by the machine tool in each operating state, in absolute and percentual scale.

The total time for hobbing one gear is 200 seconds, split into three distinct operating states: “Processing” (82.5%), “Warm up” (14.5%), and “Ready for Processing” (3.0%). Such utilization profile is typical for machine tools operating under batch production conditions, where the goal is maximizing the adding value activities in the productive chain.

4.1.2 Study of the active power employed on the hobbing

The active power and electrical energy consumption were measured every 5 seconds throughout the complete hobbing cycle of 200 seconds, by means of the device Fluke 435. Such procedure was repeated 5 times to measure the total energy consumption by the machine tool, and, the portion corresponding to the following machine tool subunits: linear and rotational drives, hobbing cutter spindle; hydraulic unit; refrigeration unit; chips extracting conveyor and oil mist filter (Fig. 8). In addition, a final measurement was done to record the energy consumption when the machine assumed typical non-productive states, such as “Extended Standby” and “Standby” operating states.

Prior to the conduction of this case study, the machine tool was assisted by the conventional flood lubrication (FL). Under that machine setup, the maintenance department monitored periodically the overall energy consumption over two years of operation, for the same gear considered in this case study. The average consumption value obtained was 0.85 kW.h.

The Table 2 shows the aggregated electric energy consumption for each machine tool operating state, as well the values converted according the defined reference flow, in Sect. 3.3.1. The major portion of energy is consumed in the operating state “Processing” (76,5%), once the serial hobbing process was designed to the highest productivity, provided the quality requirements of the machined gear. On the other hand, the “Warm-up” state presented the higher value when the energy consumption is converted into the reference flow basis. This is explained by the energy consumption peaks that take place while motion units turn into action for positioning the hob head in reference to the blanked work gear, and, during the moves of robot arm.

Table 2 – Energy Consumption per Operating State of Machine Tool

Operating State	Energy Consumption per Machined Gear [kW.h]	Energy Consumption acc. the Reference Flow [kW.h/s]	Energy Consumed [%]
Processing	0.785	0.0048	75.0%
Warm-up	0.160	0.0055	15.3%
Ready for Processing	0.018	0.0029	1.7%
Extended Standby	0.042	0.0029	4.0%
Standby	0.041	0.0028	3.9%

The Fig. 9 presents the hobbing cutter spindle speed and axial feed rates and the corresponding energy machine tool consumption resulted from the combination of both machining parameters, measured under operating state “Processing”. The assumed cutting parameters are theorical and based on the tacit knowledge from the gear production department, where the study case took place.

While keeping all other operating states unchanged, the variation in the machine tool total energy consumption was 9,4%, caused by the combined variation of those main machining parameters.

4.1.3 Consumables Study Data

The raw material consumption in form of blanked work gear from 20MnCr5 alloy, the hob cutter and the cutting fluid took place only during activation of “Processing” state, where the hob cutter exerts the cutting forces over the work gear. On this way, all the inventory results for the consumables are enclosed in this operating state of the machine tool.

For every hobbing cycle in the case study, the raw material, in form of turned part with 15 kg and 1,901.14 cm^3 of volume, is fed into the machine tool chamber room, or, 75 g of raw material according to the reference flow basis.

The consumed cutting fluid varies significantly between the conventional FL and the MQL. For the FL method, the cutting fluid is pumped into the cutting zone from a reservoir installed on the machine tool. While the cutting fluid is mixed to compressed air, and, subsequently, pumped into the cutting zone as a spray, according to MQL method. The amount of cutting fluid consumed by one machined gear was monitored over 100 hours of operation, which represents 1,532 gears machined in the regular production flow.

The hobbing process assisted by the FL method consumed 687.5 liters of cutting fluid, while, the machine-tool equipped with MQL demanded 11 liters of the cutting fluid. In terms of reference flow, 0.036 milliliters per second for FL system, and, 2.24 milliliters per second for the MQL system. It means, a reduction of 98.4% in the consumption of cutting fluid after the introduction of MQL.

The consumption of hobbing cutters was monitored over 100 hours of operation, with both assisting systems, FL and MQL. In the average, it was possible to machine 450 gears in conformity to the quality requirements of the product, before ordering reshaping and recoating of the tool. It means, each hobbing cycle a small percentage of tool Lifetime, or precisely 0.0022 hob cutter. When converting that value into reference flow basis, the amount was even smaller: 0.000011 hob cutter per second. As this consumption level is not significant for the LCI, it was not included in the LCA.

4.1.4 Emissions Study Data

The study case considered two emissions. The first one, was the filtered air exhausted from the machine tool chamber room to the Ecosphere, passing through an oil mist separator and electrostatic filtering system. The second emission was the heated air exhausted by the hydraulic oil heat exchanger.

The output filtered air measurement showed mist and fume concentration under 5 mg/m^3, while the exhaled air from heat exchanger reached 38°C at a distance of 0.5 m away from the heater. None of those emissions surpassed the thresholds established by the Brazilian Regulatory Standard NR-15 [57], according to the periodical audit carried out by the Health & Safety department of the company, which hosted the case study. Due to that reason, those emissions were considered as low relevant, and, therefore, not taken into account to the LCIA phase.

4.2 LCIA and Interpretation

The input and output data from the system “Gear Hobbing Machine”, as LCI data, were combined with background system data for modelling the LCA in the software GaBi. The gear tooth hobbing process model included the inputs: raw material consumption, electric energy output by the machine tool, and, the cutting fluid employed while machining the gears, as described in the subsections 4.1.2. and 4.1.3.

On the other hand, the hobbing process outputs included in the LCA model were the 32-teeth machined gear, the metal chips and the amount of contaminated cutting fluid extracted together with the chips.

The LCI data were extrapolated for the production of 80,000 gears in order to represent the annual volume manufactured in the gear production plant. The raw material inventory was considered into the LCA model, since the ore extraction activity, the steel making process, and, the forging and turning processes to obtain the semi-finished gear were quite relevant in terms of energy consumption. Moreover, the raw material dataset was taken from the database of the software GaBi, whose steel scrap content was near 95%.

The environmental impact analysis was performed according to the method ReCiPe 2016 v1.1 Midpoint (H) [58], available in the software GaBi, version 9.2.1.68 – Education Database 2020, at the time of analysis.

4.2.1 Sensitiveness Analysis

The LCIA included 4 scenarios, that depicted distinct production configurations for the automotive gears, as shown in Fig. 10. The proposed scenarios provided progressive reduction of inventories used in the hobbing operation, and, consequently changes on the potential environmental impacts in the eleven environmental categories listed in the subsection 3.3.3.

The Fig. 11 shows potential environmental impacts comparison for the 11 impact categories normalized according to the ReCiPe 2016 v1.1 Midpoint (H) [58], applied to the 4 proposed scenarios of gear hobbing process. The category Fossil Depletion achieved the highest score in the scale person-equivalent, showing a score 3,400 times higher than the Metal Depletion score. 4 from 11 impact categories comprise 80% of total aggregated scores of the 11 categories, in person-equivalent: Fossil Depletion (43%), Climate Changes excluding biogenic carbon (19%), Terrestrial Acidification (11%) And Freshwater Consumption (8%).

The Fig. 12 also revealed the proposed 4 scenarios produced a limited effect over the reduction of environmental impacts, in the 11 mentioned categories. The major reduction was perceived in the category Fossil Depletion (12%). Once the proposed scenarios concern only the hobbing process, the inventory reduction did not reflect on the impacts related to the raw material flow, which is characterized for intense energy consumption, such as the mining and steel-making activities.

The Fig. 12 and Fig. 13 present the contributions of product system input and output flows to the environmental impacts for the scenarios A and D, described in the Fig. 10, since their comparison represents the most significant differences in terms of unitary process inventory.

The raw material consumption, as 20MnCr5 alloy billets, is linked to more than 75% of environmental impacts, in the average of the 11 normalized categories for the 4 analyzed scenarios. As follow, in descending order: cutting fluids consumption (15%), raw material forging and turning energy output, and, gear hobbing (10%). The search for hotspots confirmed the raw material and cutting fluids flows contributed to more than 90% of the environments impacts obtained in this case study. The most relevant resources included on those flows were the energy output for the steel production (53%), lubricants production (34%) and material resources (5%). In terms of emissions, 99% of the environmental impacts were associated to CO_2, SO_2 e particulate emissions, all them derived from the steel-making process.

The introduction of MQL, and, the consequent minor cutting fluid consumption, enhances even more the relevance of raw material flows as key contributor to the potential environmental impacts, as seen in the Fig. 13.

Although the raw material appeared as the major hotspot of the unitary gear hobbing process, the handling and use of 20MnCr5 alloy semi-finished blanks has been optimized for decades over the gear production supply chain, in a way that improvements of that hotspot would be only feasible by means of gear redesign, which, in last instance, would demand new development & test validation efforts for the application on commercial vehicles. As the case study focused on the manufacturing process, the further environmental impact analysis was aimed exclusively at the consumption of cutting fluid and electrical energy by the machine tool.

The Fig. 14 presents the environmental impacts results classified according in a descending order, from the major impact reduction, for the 11 categories defined on the subsection 3.3.3, in the scale person-equivalent. 4 from the 11 categories enclosed more than 85% of estimated potential impacts, when Scenario A is compared to scenario D.

- Fossil Depletion (56,5%);
- Human Toxicity, cancer (13,4%);
- Terrestrial Acidification (7,9%);
- Climate Changes (7,7%).

In terms of LCI, the shift from scenario A to scenario D provided the reduction of cutting fluid consumption by 98,4%, and, in machine tool electric energy output by 18,7%. Without the corresponding raw material flows, the influence of machine tool energy output and cutting fluid consumption in the gear hobbing process became evident. In average of 11 impact categories, electric energy consumption is linked to 93.6% of environmental impacts, while cutting fluids accounts for 6.4% (Fig. 15). Likewise, Campitelli et al. [8] demonstrated the electric energy and cutting fluid consumption correspond, respectively, to 70% and 27% of the potential environmental impacts generated by machining processes.

The Fig. 16 and Fig. 17 show the reduction on the potential environmental impacts, as effects from the introduction of MQL and implementation of strategies to decrease gradually the energy consumption by the machine tool.

The introduction of MQL provided impacts reduction of 70.77% considering the aggregated scores of the 11 categories. Conversely, the machine tool consumed energy reached sparce 3.74% of impact reduction. Therefore, the numeric contribution of MQL at environmental impacts mitigation is 19 times higher than the effects of reducing machine tool energy output.

The Fig. 16 shows decrease of 35 points person-equivalent of the category Fossil Depletion. This result can be attributed, in particular, to the reduction of non-renewable resources, and, also to decreasing emissions to air of inorganic elements. Moreover, the category Human Toxicity - cancer, stood out from other categories, showing an impact reduction of 8.03 points person-equivalent, as effect of less emissions to air of inorganic elements due to decreased consumption of cutting fluids. In the practice, after introduction of MQL, the machine tool operators were no longer exposed to the cutting fluids and their diverse chemical toxic substances.

On the other hand, the reduced electric energy output during the hobbing operation did not show significant effects over the potential environmental impacts. Considering the aggregated normalized impacts of the 11 categories, the reduction reached only 3.3 points person-equivalent (Fig. 17). The reduction of timing in standby states (70%) and cutting power in processing state (12%) ended up reducing the machine tool energy output only by 14.6%.

4.3. Closing Remarks about LCA

The results obtained from the LCIA converged in general to the conclusions presented in the Literature Review. Fossil Depletion, Climate Changes and Terrestrial Acidification represent together, around 75% of the potential environmental impacts derived from the gear hobbing process.

The input flow related to raw material is associated to 75% of the potential environmental impacts, according to the case study, due to energy-demanding processes like mining and steel-making.

If the effects of raw material flow are put apart from the product system “Gear Hobbing”, the introduction of MQL provided approximately 70% reduction on potential environmental impacts, and, 8.6% when material flow is still considered in the analysis.

On the opposite way, Scenarios C and D together contributed only with 3.7% in the reduction of the aggregated impacts of the 11 categories.

5. Conclusions

The conduction of Literature Review and the comparative LCA for the gear hobbing process underpinned the following conclusions:

1. the methodology UPLCI, proposed by Kellens et. al [44, 45], is practical to the obtainment of inventory datasets and scalable to similar manufacturing processes;
2. LCI datasets for machining processes are not profuse in the literature, exemplary only three articles were found in the database Web of Science, when it turned to gear hobbing and LCA simultaneously;
3. the application of MQL in machining processes presents more advantages in comparison to FL, since it leads to the solid waste reduction, water consumption, machine tool energy output decrease, and, occupational health risks mitigation by the virtually elimination of contact between machine tool operator and cutting fluid;
4. the machine tool kept the operating state “Processing” in 76,5% of the unitary gear hobbing cycle, it means, effectively removing material from the blanket work gear;
5. the introduction of MQL provided a reduction of 98% in the cutting fluid consumption;
6. the hob cutter consumption, generation of solid waste and emission to air did not present relevance to the studied machining process;
7. the raw material demanded for the hobbing process contributed to more than 75% of the raised potential environmental impacts, considering the average of the 11 normalized impact categories evaluated in 4 production scenarios, while the cutting fluid use totaled 15%, and, the electric energy output from the machine tool achieved 4% only;

8. the electric energy consumed by the machine tool is not the gear hobbing process hotspot, but the raw material employed in that process.
9. the more optimized is the hobbing process in terms of productivity, the less room there will be for implementing strategies to decrease electric energy consumption by the machine tool, once reduction of cutting power will cause longer operation time, and, reduction of non-productive operating states would already been implemented.

The cutting power and energy required by the hobbing process are influenced by a dozen of parameters linked to machine tool, hob cutter and gear geometry. Therefore, the determination of the more relevant process parameters to energy consumption would require the conduction of orthogonal experiments in the mentioned machine tool. However, the access to that machine tool was limited, since the equipment operates continuously in batch production. Thus, it can be considered a limitation of the present research.

The performed case study was considered a pilot project for the hosting company, having contributed to build knowledge about LCI and LCA.

Declarations

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Conflict of interest

The authors declare no competing interests.

Availability of data and materials

The findings of this work are available within the article.

Code availability

Not applicable.

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Figures

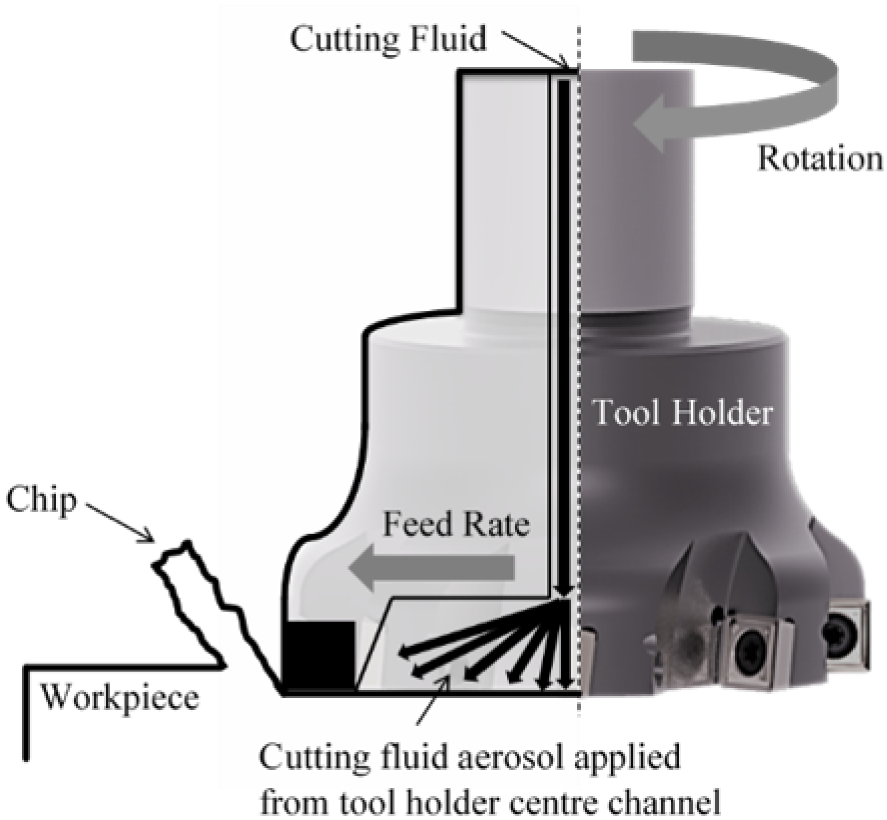


Figure 1

Hob cross section and its inner duct to the mix air-oil

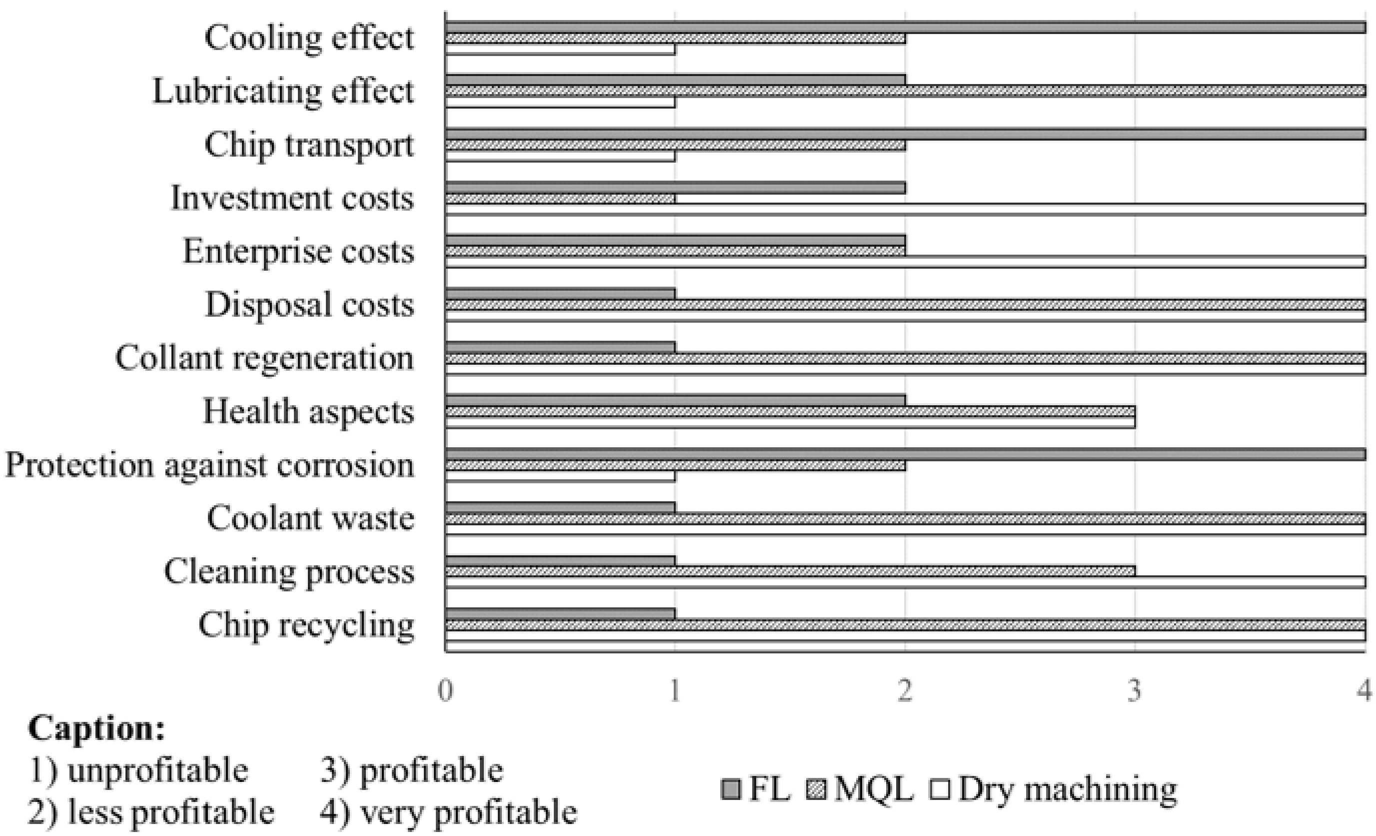


Figure 2

Comparison among lubri-refrigeration technologies for machining (adapted from Grzesik [30])

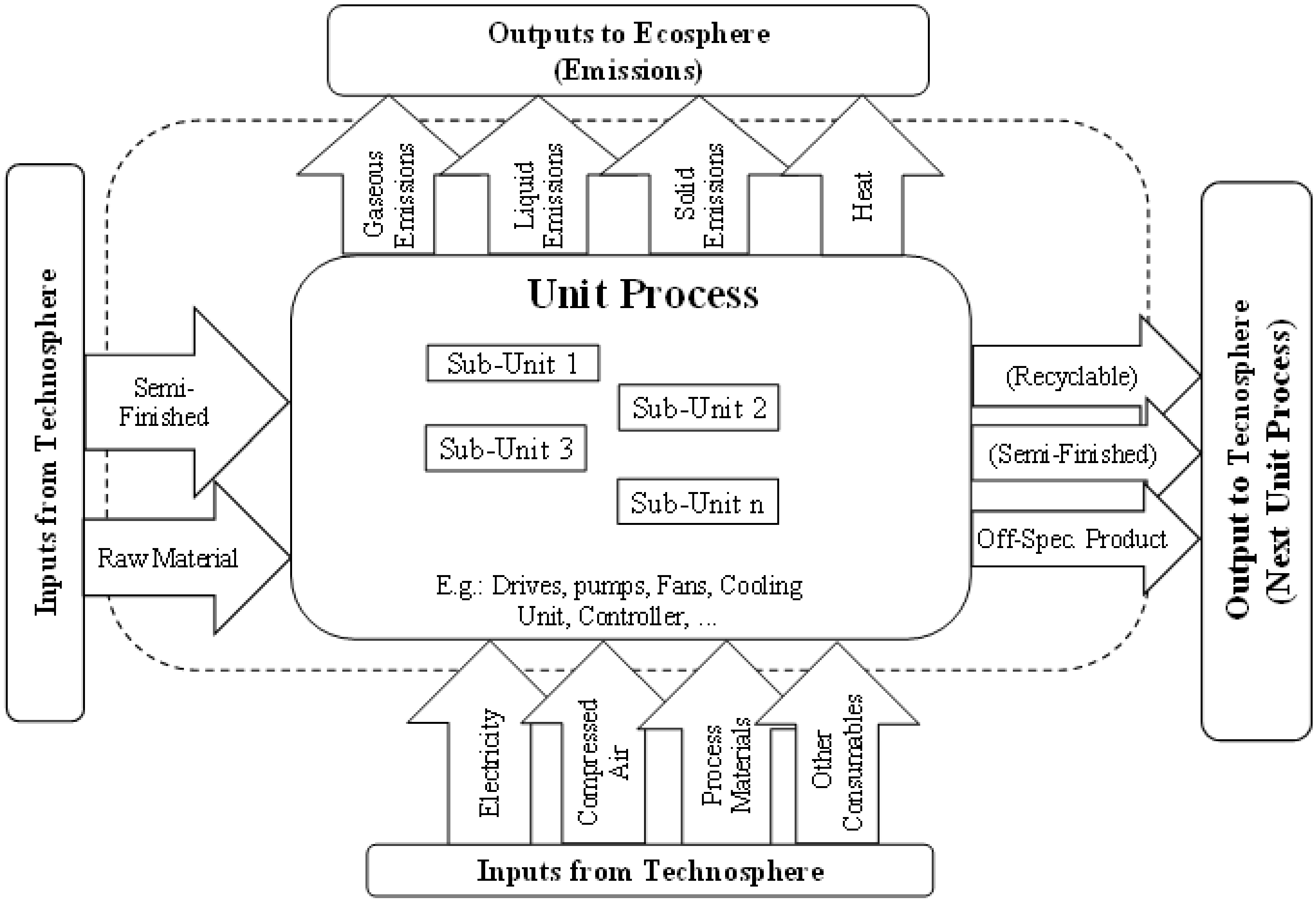


Figure 3

System boundaries of a unit process (Source: Kellens et al., [44])

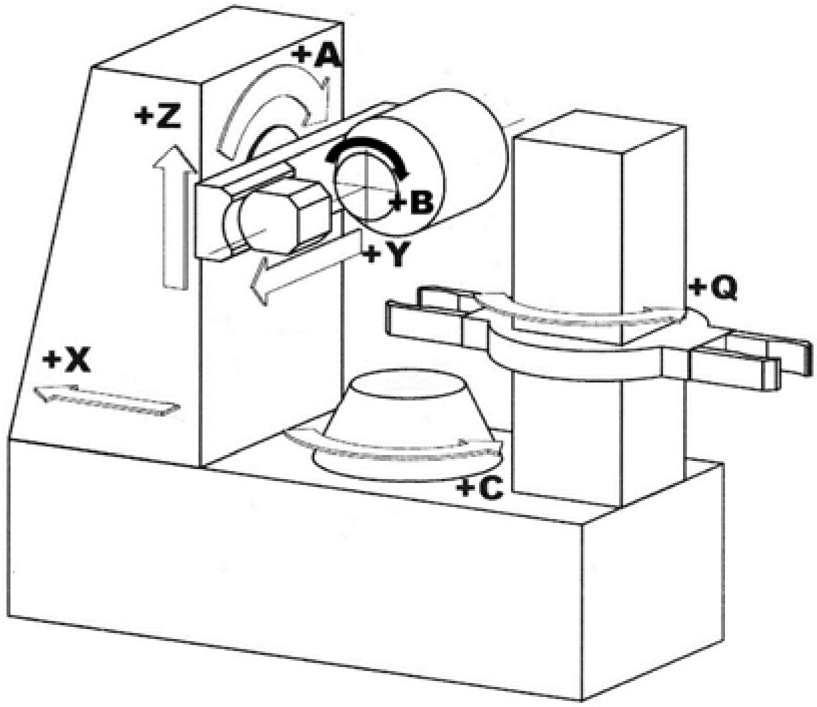


Fig. 4A

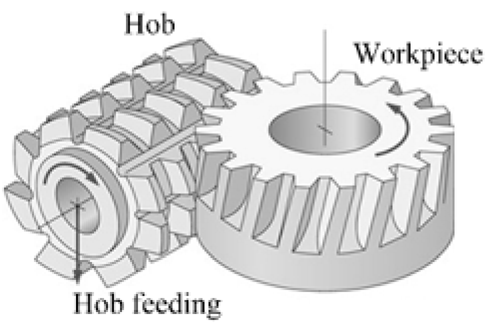


Fig. 4B

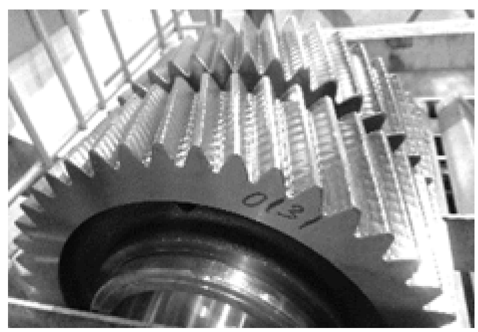


Fig. 4C

Figure 4

A – Schematic diagram of the gear hobbing machine. Source: authors) B – Schematic diagram of tool and workpiece (Source: adapted from Gupta et al. [55], 2017) C – Study case gear after bobbing operation (Source: authors)

Sub-Units	Operation States				
	PROCESSING	WARM UP	READY FOR PROCESSING	EXTENDED STANDBY	STANDBY
Mains and Machine Controls	●	●	●	●	●
Cooling System	●	●	●	●	○
Spindle and Rotating and Feed Drives	●	●	⊙	⭘	○
Exhausting System	●	●	⊙	○	○
Chips Extraction Conveyor	●	⊙	⊙	○	○
Central Compressed Air and/or Lubrication Pump	●	⊙	⊙	⭘	○

Caption:

Activated	●
Energised - Intermittent	⭘
Energised / Not activated	⊙
Off	○

Figure 5

Correlation Between Machine Tool Operation States and Sub-Units Activation

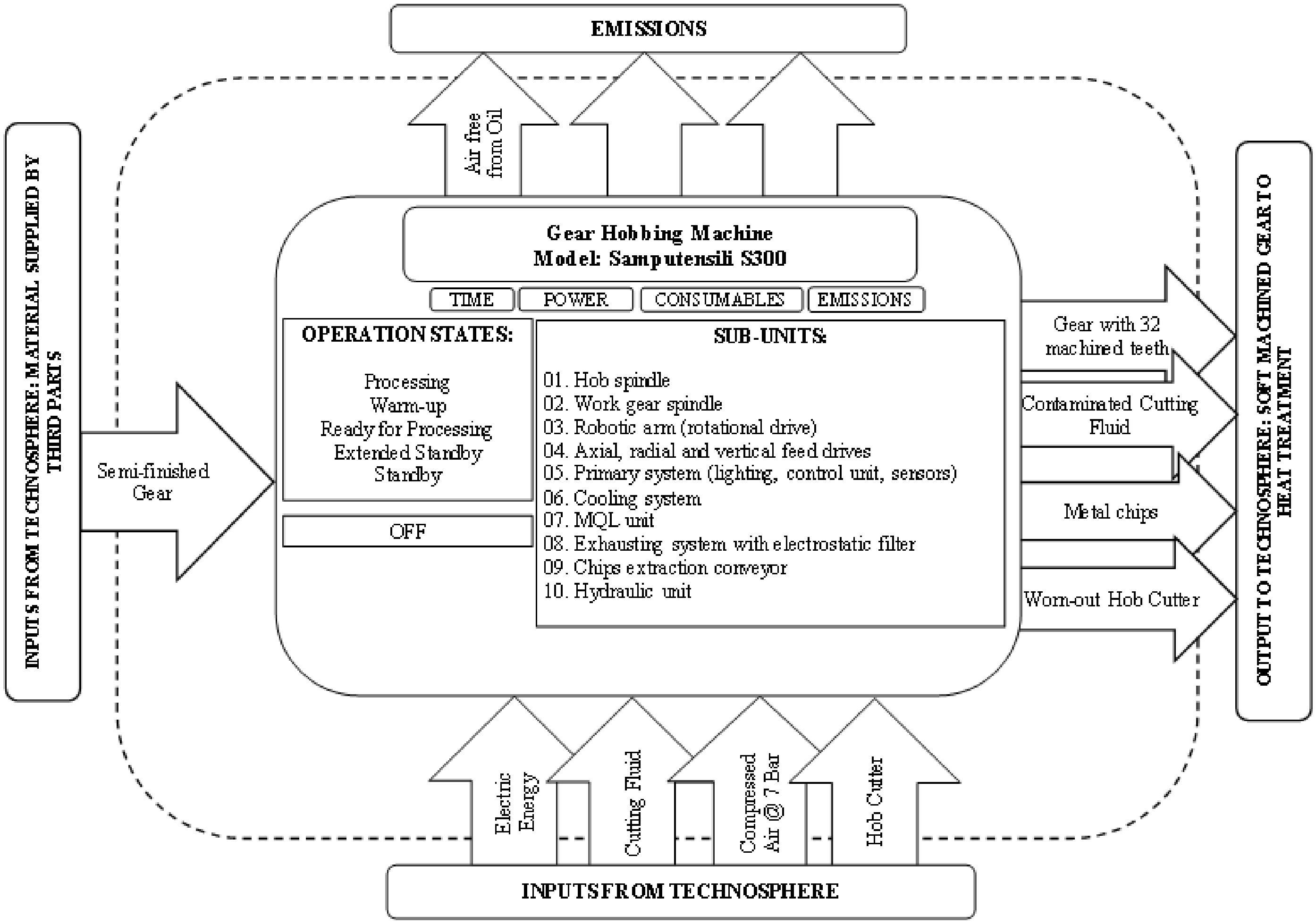


Figure 6

System “Gear Hobbing” Boundaries

Duration [in seconds]	Operating State	Acticity
0-1	*READY FOR PROCESSING*	Machine tool ready to start the hobbing cycle (at zero referential);
1-5	*WARM UP*	Drives moving towards the workpiece, and, hob cutter and worktable spindles modulating the speed;
5-135	*PROCESSING*	Rough cut;
135-140	*WARM UP*	Drives repositioning to start the second cut, and, hob cutter and worktable spindles modulating the speed;
140-175	*PROCESSING*	Finishing cut;
175-195	*WARM UP*	Drives repositioning to reference zero, and, new work piece fed by the robot arm;
195-200	*READY FOR PROCESSING*	Machine tool ready for new cycle.

Total Time in "*Processing*" state, in [s] and [%]	165	82.5%
Total Time in "Warm-up" state, in [s] and [%]	29	14.5%
Total Time in "Ready for Processing" state, in [s] and [%]	6	3.0%

Figure 7

Operating states duration for the hobbing cycle of one gear

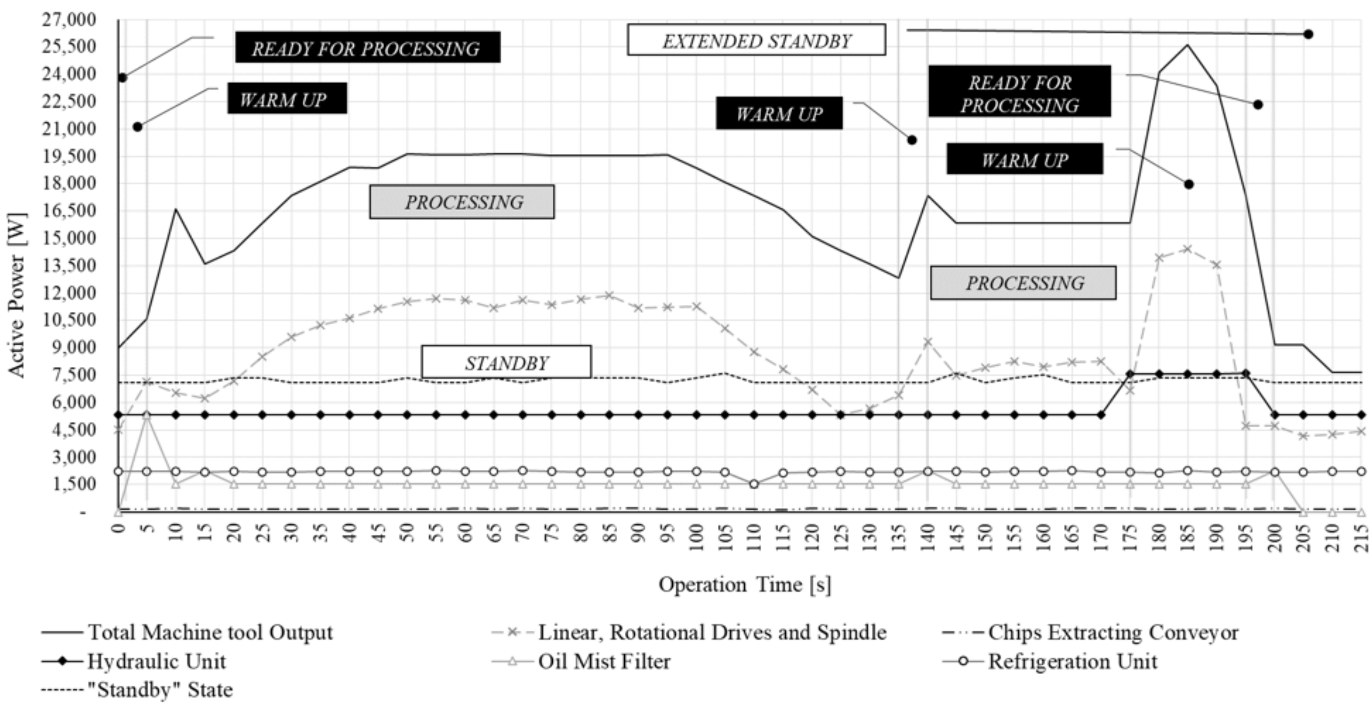
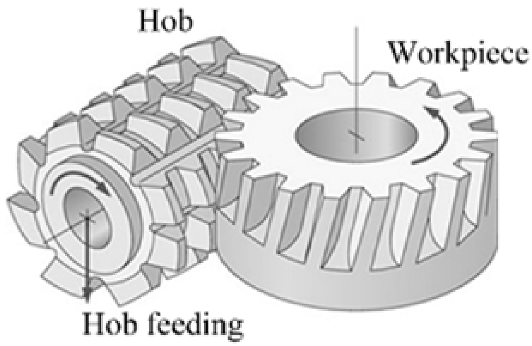


Figure 8

Active power measured during one complete hobbing cycle



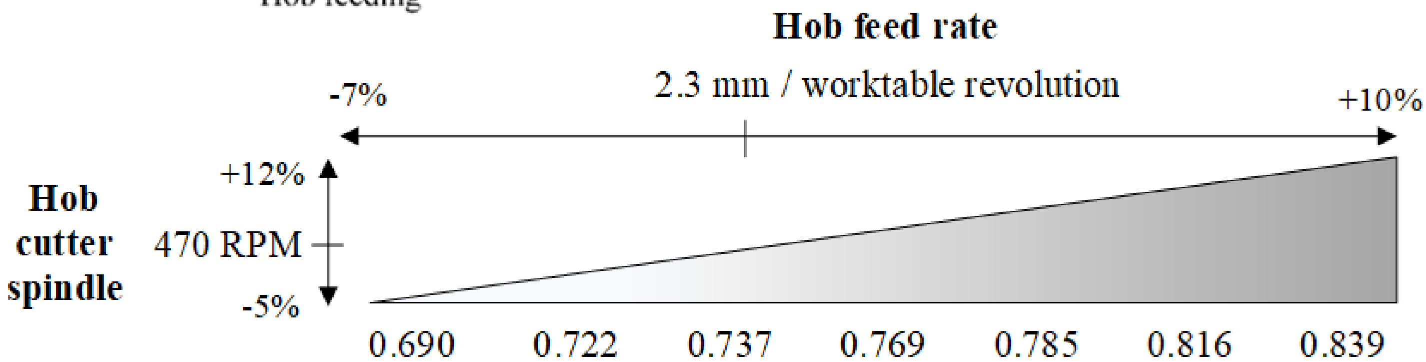


Figure 9

Energy consumption in “Processing” state for different process parameters, in kW.h

Scenario	Description
A. Flood Lubrication (FL)	Machine tool configuration valid from January 2014 till June 2018.
B. MQL	Present machine tool configuration valid since July 2018.
C. MQL and Optimized Standby State	Scenario B + Reduction of 70% in Standby and Extended Standby States
D. MQL and Optimized Standby State and reduced Cutting Power	Scenario C + Reduction of 12% in Energy Consumption under Processing State.

Figure 10

Machine tool operation scenarios for LCIA

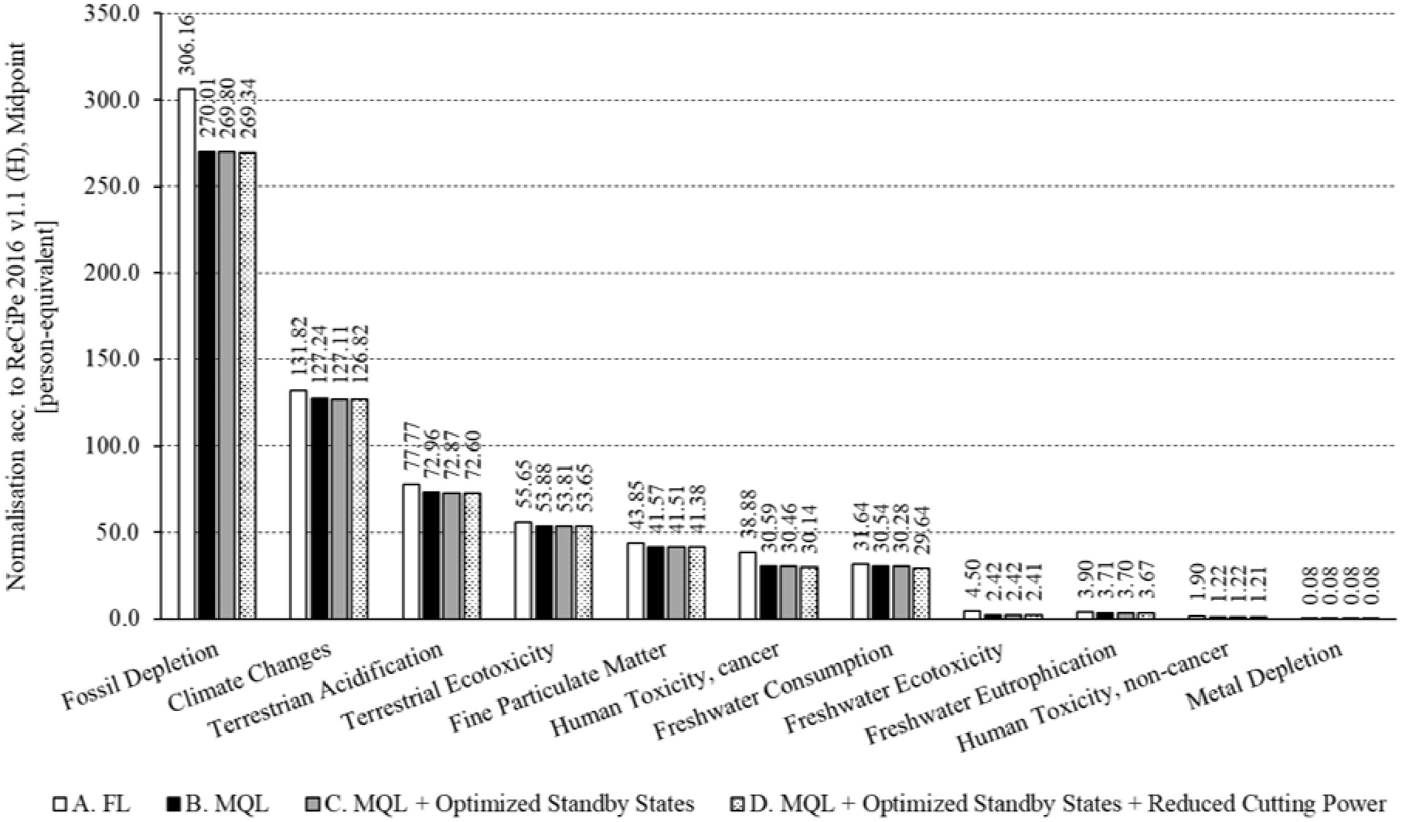


Figure 11

Normalised environmental impacts including raw material flow

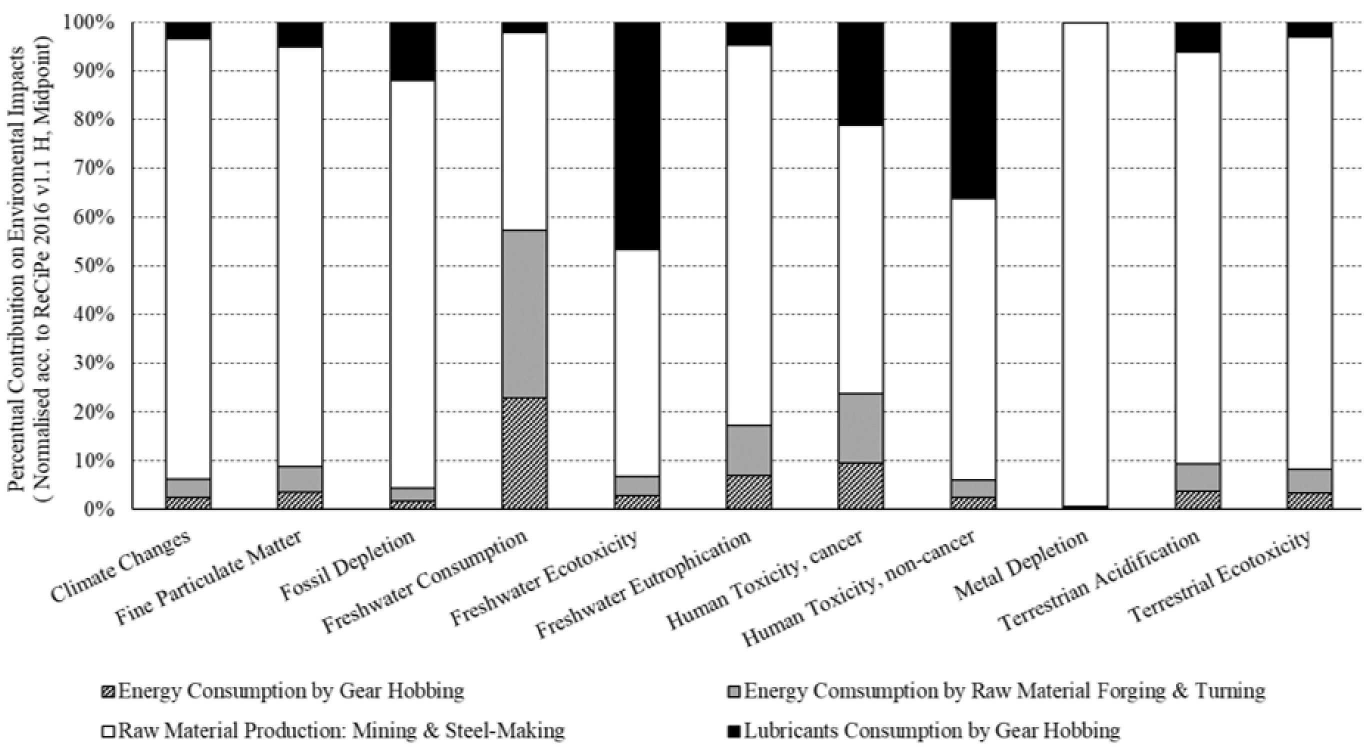


Figure 12

Contribution of input and output flows on the potential environmental impacts acc. to Scenario A

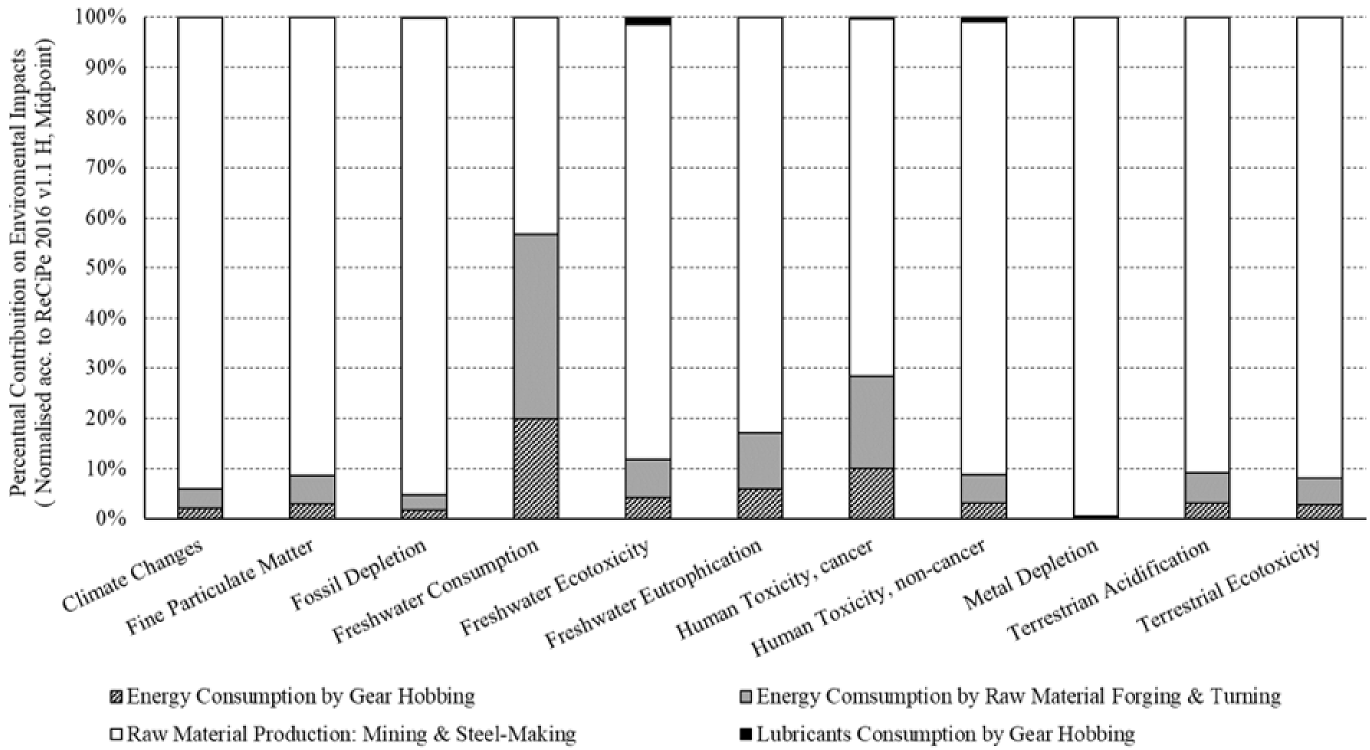


Figure 13

Contribution of input and output flows on the potential environmental impacts acc. to Scenario D

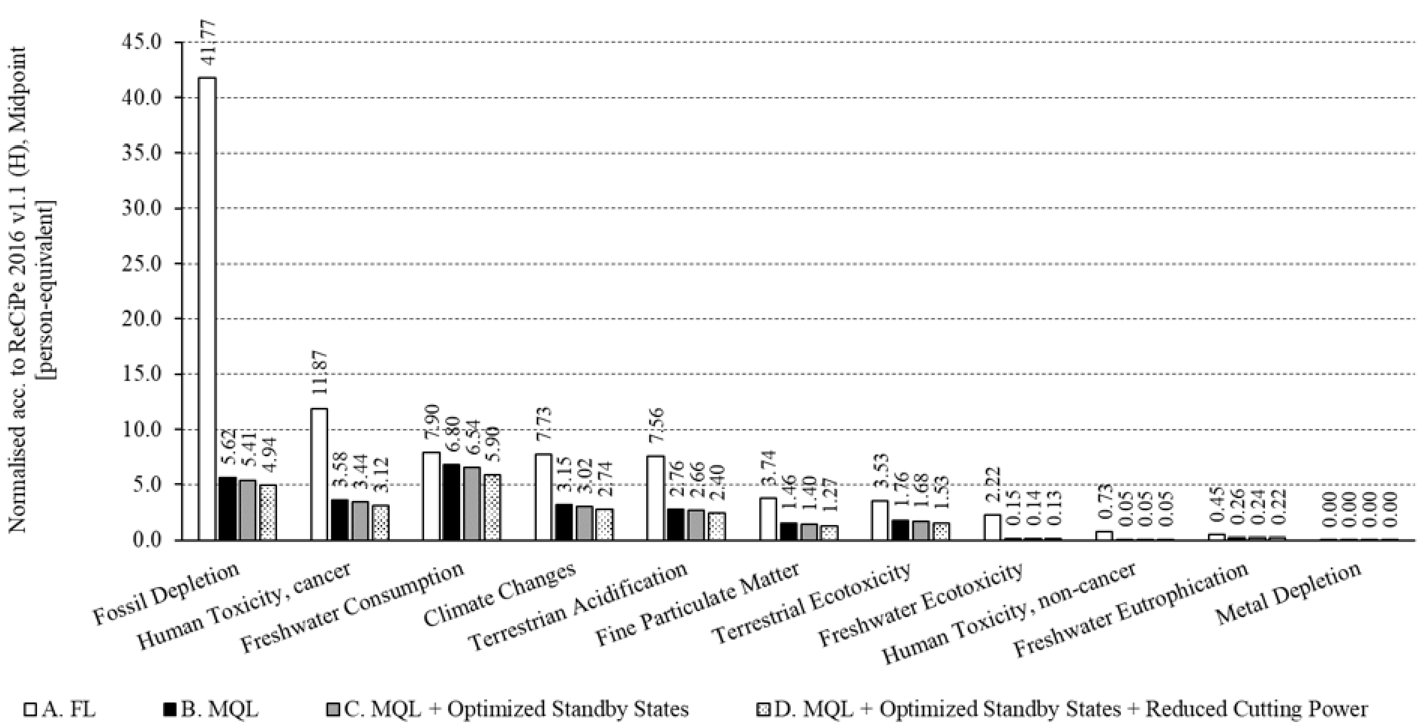


Figure 14

Contribution of input and output flows on the potential environmental impacts (except raw material raw)

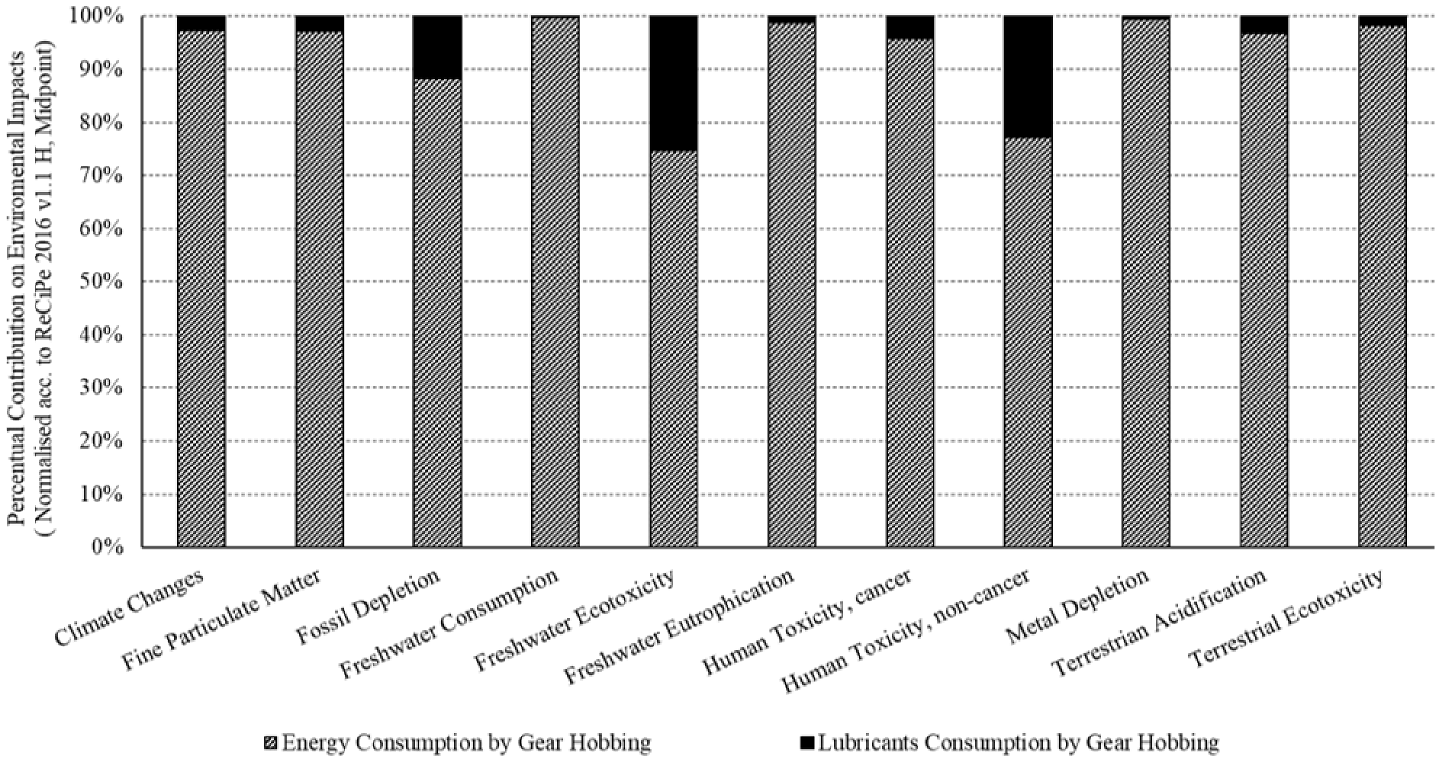


Figure 15

Contribution of input and output flows on the potential environmental impacts acc. to Scenario D (except raw material flow)

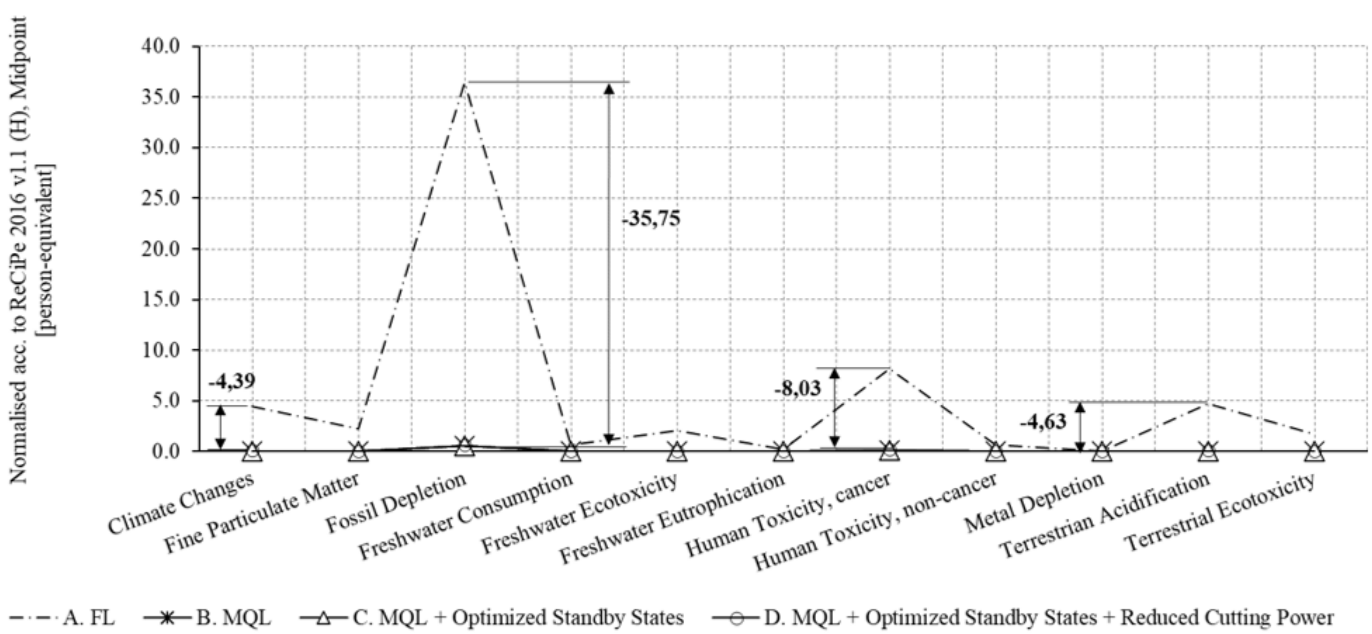


Figure 16

Effects of cutting fluid consumption reduction over environmental impacts

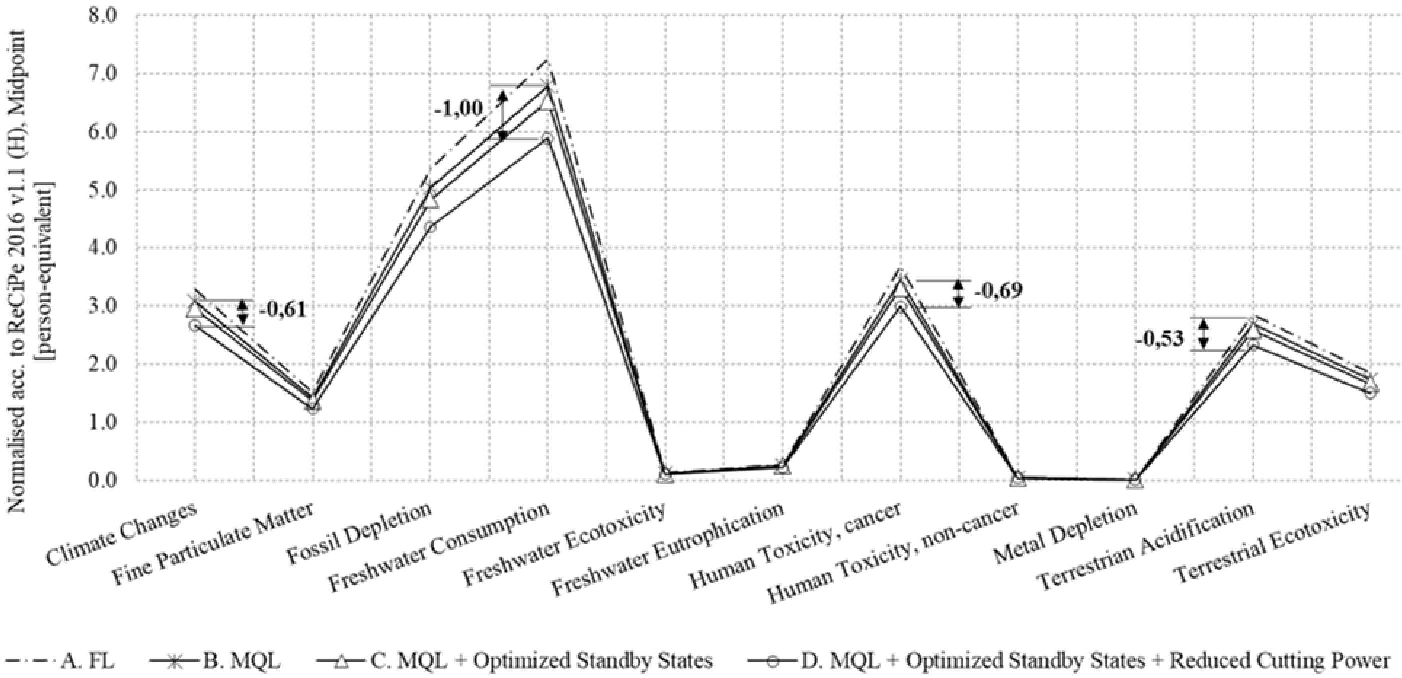


Figure 17

Effects of electric energy consumption reduction over environmental impacts