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Life Cycle Assessment in automotive sector: A case study for engine valves towards cleaner production

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ABSTRACT

Life Cycle Assessment (LCA) is a well-established tool to analyze environmental aspects and impacts of products and processes. However, there are few studies available regarding LCA of automotive components such as the small parts used by vehicle engines, e.g., intake and exhaust valves. This paper showed a cradle-to-grave LCA of exhaust valves produced in Brazil for automotive use. Based on environmental hotspots of the case study, cleaner production scenarios were developed to reduce environmental burdens and to improve manufacturing eco-efficiency. Thirteen midpoint impact categories were evaluated and more than 90% of all the impacts were due to fuel consumption into the internal combustion engine during the valves use phase. Regarding the valves manufacturing phase, the machining processes applied on the valve stem represented 63% of all the impacts, and they were strongly influenced by the consumption of electric energy, raw materials used in the valve stem and cutting fluid. For this reason, cleaner production scenarios were evaluated and tested in a centerless grinding process of the valve stem. The best cleaner production scenario showed a potential impact reduction up to 72% in the stand-by grinding mode followed by up to 44% less impacts in the dressing mode. Simple changes on grinding parameters produced a huge potential of minimizing environmental burdens in a life cycle perspective, especially in terms of impacts for resources (fossil and minerals) depletion (RD). A comparison between the environmental profiles before and after adopting the proposed cleaner production measures showed a significant reduction of 27% on the RD impacts. Therefore, improvements of the exhaust valve's manufacturing parameters can generate a better environmental life cycle performance towards cleaner production.

1. Introduction

There are important initiatives aimed to prevent and minimize environmental impacts resulting from manufacturing, such as Cleaner Production (CP) (UNEP, 2002; Oliveira et al., 2016, 2017). However, besides the environmental benefits from CP, a gap regarding the quantitative environmental impact assessment of manufacturing processes still exists, particularly about the resources efficiency of energy and materials in a Life Cycle Thinking (LCT) (Dornfeld et al., 2013). To this end, Life Cycle Assessment (LCA) appears as a well-established tool to address this issue (EC/JRC/IES, 2010; Kellens et al., 2012a, b; Silva et al., 2016).

According to Linke et al. (2012), Zendoia et al. (2014) and Shin et al. (2017), in order to improve manufacturing processes and to achieve real and relevant environmental benefits, companies should go further than the limits of their manufacture phase of products, and look at the LCT.

Manufacturing phase of products has a key role in accounting for the environmental impacts caused throughout a product life

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cycle (Duflou et al., 2011; Dornfeld, 2014). However, the importance of manufacturing phase in a LCT may vary considerably depending on the type of a product, its main components and materials (Aurich et al., 2013; Dornfeld, 2014).

For the automotive industry, Warsen and Krinke (2013) highlight that environmental impacts of the use phase of automotive vehicles often outweigh the impacts from their components manufacturing and the assembling of a vehicle itself. In such cases, the use of LCA is strongly recommended to identify the environmental hotspots along the complete life cycle of products. In this sense, Table 1 summarizes a recent literature review on the use of LCA in automotive industry.

It is important to note that publications from Table 1 were from European countries, followed by China and United States, and other economies, e.g., Brazil, are not fully investigated, and this gap was a motivation for current paper proposal.

From Table 1, it was observed that most of the environmental hotspots in the automotive industry are associated with the vehicle's use phase, mainly due to the global warming potential and energy demand (fuel consumption). The post-use phase is mainly affected by the end-of-life strategies selection for materials and components recovery to the automotive industry, and this choice also reflects on the environmental impacts of manufacturing phase. The manufacturing phase is affected mainly by electric energy consumption and resources efficiency of manufacturing processes.

Dornfeld (2014) and Helu et al. (2011) suggest that there is a potential for life cycle improvement in leveraging manufacturing precision of automobiles components. According to these authors, the efficiency in fuel consumption can be improved, for instance, by the optimization of the surface roughness in automotive gearing systems used in internal combustion engines. Thus, improving manufacturing processes precision may have a direct influence on the fuel consumption in the use phase of a vehicle.

It is important to highlight that most of the studies from Table 1 are focused on the vehicle itself, engines, use of light materials and/or recycling approaches. However, no study was found for automotive small parts, for instance, the engine valves used in fuel intake and exhaust of combustion gases. A proper operation of the valves is crucial for the combustion process in the use phase of vehicles (Taylor, 1998). Malfunctioning on sealing of the combustion chamber can result in relevant losses of compression, power, and engine performance in lifetime (Ramalho et al., 2009). For this reason, automotive valves are essential elements of a motor vehicle and a LCA study could assist to enhance knowledge about their environmental life cycle performance.

Therefore, in order to contribute to spread further studies on LCA in automotive sector, the aim of this paper is to perform a cradle-to-grave LCA study for automotive engine valves produced in Brazil, identifying environmental hotspots and suggesting cleaner production scenarios.

This paper is organized as follows: materials and methods are described in section 2. The cradle-to-grave LCA results are discussed in section 3. The main environmental hotspots are identified in section 4, and they are used to list some cleaner production scenarios to reduce life cycle environmental impacts by improving manufacturing resources efficiency of the valves. Finally, the conclusions and outlooks are presented in section 5.

2. Materials and methods

The methodology adopted was the case study (Yin, 2015), because it is the most suitable design for investigation of a contemporary phenomenon within its real context. The case study was applied for a company that produces engine valves in Brazil, and its identity was preserved due to privacy issues.

The chosen research methodology included:

- **Literature review:** as presented in Table 1, publications involving theoretical and practical studies on LCA for automotive industry were searched and analyzed in order to gather relevant technical information for the present study. The literature results were used on section 4 to support suggestions of cleaner production alternatives to produce engine valves;
- **Definition of the engine valve model:** as a company may have many different products, a Prioritization Matrix was developed to support the valve model selection. The matrix was based on the Gravity Urgency Tendency (GUT) method, which is commonly applied for decision-based processes with low availability of accurate data (Silva et al., 2013; Tague, 2004);
- **Field data collection:** it consists of analyzing technical documents and standards used by the company, and interviewing its representatives. Each of these activities is detailed in Table 2, and the questionnaire template used for the interviews is available in Appendix 1, as supplementary material;
- **LCA of the engine valve model**: the ISO 14040 standard series (ISO, 2006a, b) were adopted to evaluate a cradle-to-grave LCA study of the selected engine valve model. More details are described in sections 2.2–2.4;
- **Selection of cleaner production scenarios**: from the LCA study results, environmental hotspots were identified. To address some of these hotspots, cleaner production scenarios were defined and tested in Section 4.1.

Table 2 shows the strategies defined for the field data collection procedure, as previously discussed.

2.1. Automotive engine valves key points

Automotive engine valves are parts of internal combustion engines and are present in most of the existing motor vehicles. They can be used to control the intake of fuel and air mixture inside the engine cylinder (intake valves), or they can serve to control the exhaustion of the flue-gases after combustion (exhaust valves).

Regarding engine efficiency, mechanical losses due to valve operation are not very representative, accounting for less than 1.5% of all energy produced by combustion (Taylor, 1998). Still, proper function of the valves is critical to the combustion process because it can affects fuel efficiency and engine performance in lifetime. For this reason, automotive valves are usually made of refractory alloys, such as stainless steel, which avoids wearing due to the high temperatures of the combustion chamber (Ramalho et al., 2009).

Fig. 1 shows some applications of intake and exhaust valves in different automotive vehicles.

Fig. 2 presents the main constructive characteristics of an automotive engine valve. These characteristics (i.e., D, d, L, and ø) and the material used to produce the valves (e.g., steel alloys, superalloys) may vary according to the function the valve will perform (intake or exhaustion), as well as the characteristics of the automotive vehicle itself (e.g., cylinder material, type of fuel, engine application).

Table 3 shows the Prioritization Matrix used to select the product configuration of interest. In order to best fit the aiming of this study, the three criteria of GUT (Gravity, Urgency, Tendency) were replaced by R, T, C, E, as follows:

- **Representativeness (R):** relative importance of a product in the total revenue of the company. 1 - low contribution; 3 - intermediate contribution; 5 - high contribution;

Table 1
Recent LCA studies in automotive sector (2013–2017).

Authorship	Purpose	Functional Unit	Environmental hotspots and highlights
Warsen and Krinke (2013)	Cradle-to-grave LCA of a Volkswagen vehicle	Service life 150,000 km	■ **Manufacturing Phase:** steel production and forming processes accounted for approximately 20-60% of all impacts (acidification, eutrophication, global warming and photochemical ozone formation). ■ **Use Phase:** vehicle-related variables on fuel consumption: - Abrasion/electronics (3%) - Aerodynamics (19%) - Powertrain (42%) - Rolling resistance (13%) - Weight (23%)
Li et al. (2013)	Cradle-to-grave LCA of a diesel engine produced in China	300,000 km driven by using a WD615-87 diesel engine	■ **Manufacturing Phase:** 0-2% of all the impacts. ■ **Use Phase:** 94-98% of all the impacts (primary energy demand, global warming, acidification, eutrophication and photochemical ozone formation).
Dhingra and Das (2014)	Cradle-to-grave LCA of downsize and light material strategies for engine parts	One gasoline-fueled engine with a power output of 225 hp used in a mid-size car over 120,000 miles	■ **Manufacturing Phase:** 2% of all energy use. ■ **Use Phase:** 98% of all energy use. ■ **End-of-Life:** recycling was responsible for a life cycle reduction of 1-2% energy use.
Raugei et al. (2015)	Cradle-to-grave LCA regarding lightening strategies for car major parts (engine excluded)	A generalized C segment passenger vehicle, considering 150,000 km of driving	■ **Raw Materials Supply:** more relevant for human toxicity, followed by acidification impacts. ■ **Use Phase:** relevant for non-renewable cumulative energy demand and global warming impacts, followed by acidification impacts.
Nakano and Shibahara (2017)	End-of-life LCA for vehicle recycling processes in Japan	The recycling of one end-of-life vehicle (ELV)	■ **End-of-Life:** global warming impacts were ~320 kg-CO_2-eq. lower due to the use of the recycling method with advanced dismantling, and ~120 kg-CO_2-eq. lower than using the shredding method.
Hao et al. (2017)	Cradle-to-gate LCA of a passenger vehicle manufactured in China	Production of a mid-size (comparable to the B-class) internal combustion engine passenger car	■ **Raw Materials Supply**: components production (car body system, powertrain system, transmission system and chassis system) has accounted for 75% of the global warming impacts.
Raugei et al. (2014)	Cradle-to-grave LCA to evaluate the potential environmental benefits of a novel hot forming process in automotive manufacturing	One complete floorpan for a C-class passenger vehicle, considering 150,000 km of driving	■ **Raw Materials Supply:** relevant for all the categories (cumulative energy demand, global warming, acidification, and human toxicity). ■ **Use Phase:** relevant for cumulative energy demand, global warming and acidification. ■ **End-of-Life:** aluminum recycling has showed a great opportunity for impacts minimization for all the environmental categories.
Li et al. (2016)	End-of-life LCA for vehicle recycling and remanufacturing processes in China	A Corolla taxi manufactured by Tianjin FAW Toyota Motor Co., Ltd.	■ **End-of-Life:** recovery process offers significant environmental benefits for all the evaluated impacts (resources abiotic depletion, acidification, eutrophication, global warming, human toxicity, and photochemical ozone creation).
Delogu et al. (2016)	Cradle-to-grave environmental and economic LCA of an automotive dashboard panel	An automotive dashboard panel, supporting and housing all the instrumentation for the vehicle use, to be assembled on Alfa Romeo Mito 955 diesel engine, with a lifespan of 150,000 km	■ **Raw Materials Supply:** relevant for all categories, excluding ecotoxicity. ■ **Use Phase:** relevant for resources abiotic depletion, acidification, eutrophication, global warming, photochemical ozone creation, primary energy demand, ozone depletion, ecotoxicity and human toxicity. ■ **End-of-life:** recycling showed a relevant potential for minimizing impacts for ozone depletion, human toxicity, ecotoxicity and acidification.
Cecchel et al. (2016)	Cradle-to-gate LCA of a high-pressure die-casting safety-relevant automotive component	Manufacture of 250 units of high-pressure diecasting aluminum suspension beams	■ **End-of-Life:** 42% of the total energy is recovered taking into account aluminum recycling scenario.
Davidson et al. (2016)	Cradle-to-grave LCA of lead-based automotive batteries	One lead-based battery with the capacity of 70 Ah applied to vehicles used for 150,000 km	■ **Manufacturing Phase:** lead production was the dominant contributor to the environmental impacts associated with the production of lead-based batteries, ranging from 50 to 60% of the global warming impacts from manufacturing, for example. Still, manufacturing impacts has low relevance compared to the use phase. ■ **Use Phase:** it was the most relevant life cycle phase for all the impact categories (resources abiotic depletion, acidification, eutrophication, global warming, photochemical ozone creation, and primary energy demand). The reduction of fuel consumption may range from 2 to 10% in the use phase depending on the battery technology and vehicle type.
Sun et al. (2017)	Cradle-to-grave LCA of different automotive engine hood designs	The transportation service of an engine hood used in a passenger car over its lifetime of 150,000 km.	■**Manufacturing Phase:** manufacturing of advanced high strength steel hood showed the lowest impacts for all the categories. ■**Use Phase:** relevant for all the impact categories (cumulative energy demand, and global warming).
Akhshik et al. (2017)	Cradle-to-grave LCA and cost analysis for a hybrid bio-based composite engine beauty cover	An engine beauty cover to be used in a generic V6 engine of a Ford SUV/pickup truck to provide cosmetic appeal, isolate the heat from the engine, and to reduce noises for 290,000 km.	■**Manufacturing Phase:** hybrid composite outperforms in all the impact categories from 21 to 80% (acidification, eutrophication, global warming, photochemical ozone formation, ozone depletion, ecotoxicity and human toxicity).

Table 2
Main strategies for the field data collection.

Collection instruments		Data source
Interview with company representatives	Based on Appendix 1, semi-structured questionnaires with open-ended questions were designed. These questionnaires were sent to the technical team of the company, composed of product engineers and environmental engineers, and data were collected as follows: - Characteristics of the company's products (mix of products, plant production capacity, market share on domestic markets and exports); - Definition of the main types of engine valves and selection of the product of interest (Table 3); - List of materials used and their quantities to produce the engine valve model of interest (Table 5); - Logistics flow mapping of the selected product and the main inputs to produce engine valves (Table 7) - Product end-of-life strategies definition for the engine valve model under analysis (recycling, landfill, etc.).	
Analysis of standards and company's internal documents	Analysis of technical documents and standards of the company: - Chemical composition of the selected engine valve model and its main physical and mechanical properties; - Mapping of the production system of the engine valve model (Fig. 4); - Records of resources consumption (materials and energy) and waste generation (solid waste, wastewater and air emissions) to produce the engine valve model under study.	

- **Trend (T):** what is the market trend for the product sales volume? 1 - Decay or withdrawal from the market; 3 - keep at the same level; 5 - increasing sales;
- **Cost (C):** cost of production (from acquisition of raw materials to product shipment): 1 - low cost; 3 - intermediate cost; 5 - high cost;
- **Environment (E):** Expected environmental impact that a product can generate from its complete life cycle: 1 - low impact; 3 – intermediate impact; 5 - high impact.

All valve models in Table 3 were classified according to the variables: type of vehicle (two-wheeled, four-wheeled, and six-wheeled vehicles); type of fuel (ethanol, diesel, gasoline); valve function (intake and/or exhaust); and valve composition (alloy steels, chrome-silicon (S) steels, austenitic chrome-nickel-manganese (A) steels, high alloys, and super-alloys).

From Table 3, it was verified that model Nº 3 (four-wheeled vehicles; gasoline; valve made of S steel and super-alloy; exhaustion) was the most relevant product, in accordance with the final ranking result. Thus, the valve model chosen for the case study was an exhaustion-type valve, designed for four-cylinder gasoline engines, used in four-wheeled vehicles, and made of chrome-silicon steel and super-alloy. According to the manufacturer, 14,000 valves of this type are produced per day, representing 40% of the plant market share and exports.

Once concluded the valve model selection, a LCA study was conducted for valve model Nº 3, following the directives described by the ISO 14040:2006 and 14044:2006 standards. The structure of the study was divided in four steps: Goal and Scope Definition; Life Cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation.

2.2. Goal and scope definition

The LCA goal was defined as the identification of environmental improvements for the exhaust valve life cycle. Table 4 presents the product definition and its function, as well as the study functional unit and reference flow:

For the above-mentioned functional unit and reference flow, Fig. 3 presents the cradle-to-grave product system overview, composed of four different life cycle phases: raw materials supply; manufacturing; use; and post-use.

The raw materials supply phase provides the inputs required for all the other life cycle phases. As can be verified in Fig. 3, the use stage was split in two parts: the first one ("Use 1") represents the use of the exhaust valves on the motor vehicle assembling process. The motor vehicle production process itself was not considered in the present study, due to the lack of LCA data for motor vehicles in Brazil. Therefore, it was assumed just the activities related to the distribution of the exhaust valves from the valve producer to the motor vehicle manufacturer.

The second part ("Use 2") represents the use of the motor vehicle itself by a final consumer (and, consequently, the use of the exhaust valves). Finally, the post-use phase accounts for the environmental impacts from the recycling of the used valves as metal and unsorted scrap prepared for melting.

To produce four exhaust valves defined by the reference flow, four different processes were considered in the manufacturing stage. Fig. 4 shows a detailed flowchart of the manufacturing system for engine valves, including the main inputs and outputs. Quantification of input and output flows for each unit process will be discussed further.

In Fig. 4, Inconel 751 and Silchrome 1 are, respectively, the

Table 3
List of products and selection of the engine valve model.

Nº	Mix of products	R	T	C	E	R x T x C x E	Ranking
1	Two-wheeled vehicles; gasoline; S and A steels; intake and exhaustion	1	5	1	1	5	6°
2	Four-wheeled vehicles; gasoline; S and A steels; exhaustion	3	3	3	3	81	4°
3	**Four-wheeled vehicles; gasoline; S steel and super-alloys; exhaustion**	**5**	**5**	**5**	**3**	**375**	**1°**
4	Four-wheeled vehicles; ethanol/gasoline; S and A steels; intake and exhaustion	3	3	3	3	81	3°
5	Four-wheeled vehicles; ethanol/gasoline; S and A steels and alloy steels; intake and exhaustion	3	3	3	3	81	3°
6	Four-wheeled vehicles; ethanol/gasoline; A steel and alloy steels; exhaustion	3	3	3	3	81	3°
7	Four-wheeled vehicles; gasoline; S and A steels and high alloys; intake and exhaustion	3	3	3	3	81	3°
8	Four-wheeled vehicles; ethanol/gasoline; S and A steels and high alloys; intake and exhaustion	3	3	3	3	81	3°
9	Four-wheeled vehicles; gasoline; A steel; exhaustion	1	1	3	3	9	5°
10	Six-wheeled vehicles; diesel; S and A steels and super-alloys; intake and exhaustion	3	1	5	3	45	4°
11	Six-wheeled vehicles; diesel; S and A steels and high alloys; intake and exhaustion	3	3	5	3	135	2°

Bold values signifies the final result of scores for product Nº 3, which was used as a baseline for the case study under investigation.

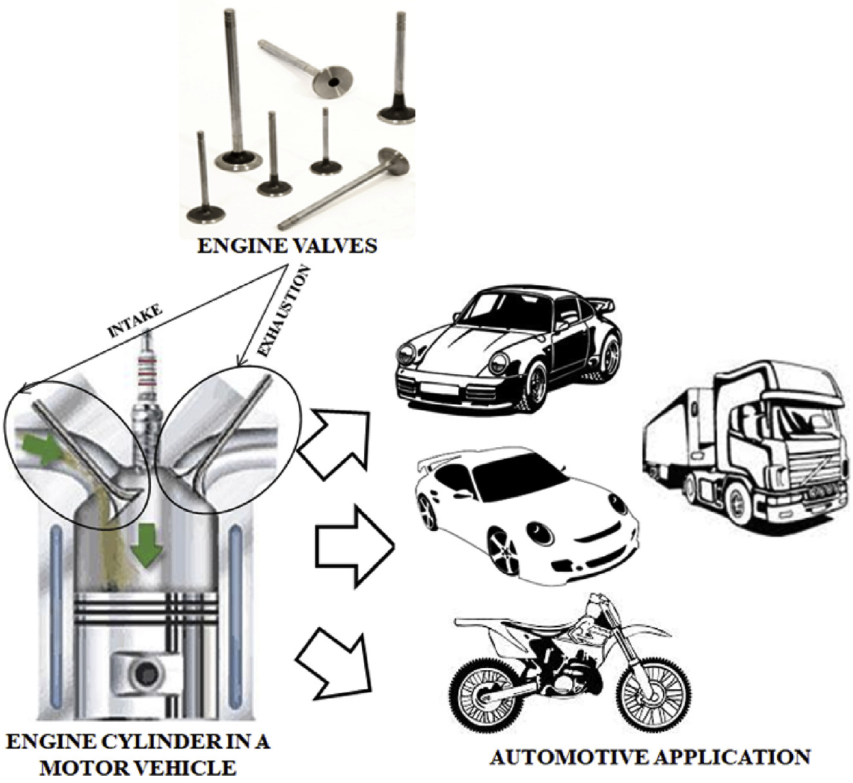

Fig. 1. Engine valves and some applications.

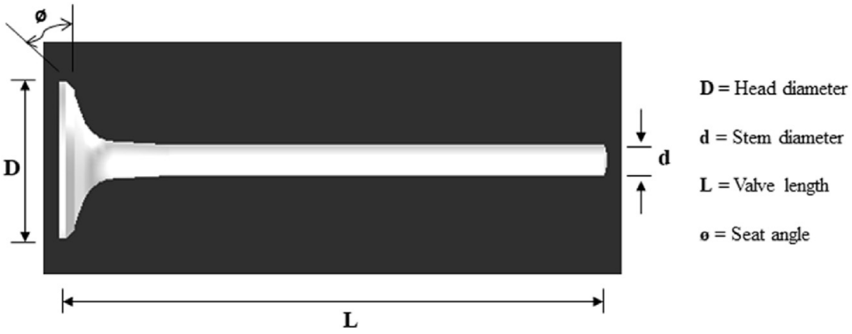

Fig. 2. General constructive characteristics of an automotive engine valve.

super-alloy and the chrome-silicon steel used to produce the exhaust valves under analysis. The first one is the basic material of the valve stem, while the second one is used to manufacture the valve head.

It is important to note that the four different processes in Fig. 4 are black-boxes due to the difficulties to gather quantitative input/output data at the most disaggregated level. Black-boxes are aggregated processes composed of two or more different operations (e.g., machining processes). Regardless the data availability, Figs. 5–8 provide more details of these aggregated processes.

Fig. 5 shows the production of metal billets divided into three operations: cutting, extrusion and minting. The first operation has the purpose of cutting 3–6 m length metal bars in smaller pieces called billets. The bars are considered as raw materials in the production of engine valves, and they can be made from different types of materials, such as alloy steels, high alloys and super-alloys.

The billets cutting occurs at temperatures of 300–900 °C, depending on the bar composition. The billets are then extruded and minted. Billets are placed in a mold/matrix and then they are mechanic conformed by a hydraulic press. The extrusion produces the conformation of the valve stem while the minting conforms the valve head.

Other manufacturing operations involve some thermal treatments (solubilization) after minting and valve washing. After billet production, the stem machining processes start (Fig. 6). First there is the straighten of the stem to ensure its parallelism. The next operations are the stem cutting followed by stem welding (friction welding). A welded stem is produced because the exhaust valve under analysis is a bi-metallic valve.

After welding, welding sharp edge machining is performed to remove excess material on the stem. The total length of the stem is adjusted by using an abrasive saw at the stem tip cutting. Lastly, a centerless grinding process using aluminum oxide grinding wheels is applied for stem finishing. All these machining operations use mineral oil as cutting fluid.

Other manufacturing operations not presented by Fig. 6 are the coating of the stem with a solution based on chromium and additives (e.g., degreaser, alkaline stripper), and further stem thermal

Table 4
Product, function, functional unit and reference flow.

Product	Function	Functional Unit	Reference Flow
Exhaust valve made of S steel and super-alloy, designed for four-cylinder gasoline engines, and to be used in four-wheeled passenger vehicles.	Seal the cylinder combustion chamber during combustion process, and control the release of flue-gases after ending of combustion.	Seal the combustion chambers and control the release of flue-gases in a four-cylinder gasoline engine of a passenger vehicle during 300,000 km of drive.	Manufacturing of four exhaust valves made of S steel and super-alloy

Table 5
Life cycle inventory to produce the exhaust valve model under study.

Phase		Input		Output	
Manufacturing	Billet Production	■ Electricity	2311.6 J	■ Metal chips of Inconel 751	11.6 g
		■ Inconel 751	155.6 g	■ Metal chips of grinding wheel	0.8 g
		■ Lubricants	1.2 ml	■ Used lubricants	1.2 ml
		■ Grinding wheel (aluminum oxide)	0.8 g		
	Stem machining	■ Electricity	22,289.2 J	■ Metal chips of Inconel 751	7.6 g
		■ Lubricants	114.8 ml		
		■ Silchrome 1	46.4 g	■ Metal chips of Silchrome 1	8.0 g
		■ Water	800.0 ml		
		■ Chrome	2.0 ml	■ Metal chips of grinding wheel	5.2 g
		■ Alkaline degreasing	0.8 ml		
		■ Alkaline stripper	1.6 ml	■ Liquid effluent	918.0 ml
		■ Grinding wheel (aluminum oxide)	5.2 g		
	Head machining	■ Electricity	16,720.8 J	■ Metal chips of Inconel 751	25.4 g
		■ Lubricants	86.8 ml	■ Metal chips of Silchrome 1	2.2 g
		■ Chemical powder	17.2 g	■ Metal chips of grinding wheel	13.6 g
		■ Grinding wheel (cubic boron nitride)	0.01 g	■ Chemical powder waste	3.2 g
		■ Grinding wheel (aluminum oxide)	13.6 g	■ Used lubricants	86.8 ml
	Finishing & packaging	■ Electricity	1003.2 J	■ Used lubricants	2.8 ml
		■ Lubricants	2.8 ml		
		■ Cardboard box	15.2 g		
	Other	■ Diesel[a]	2.0 g	■ Carbon dioxide (CO_2)[a]	6.4 g
				■ Carbon monoxide (CO)[a]	1.3E-05 g
Use	“Use 1″	■ Exhaust valves	176.4 g	■ Carbon dioxide[a]	23.2 g
		■ Diesel[a]	1.4 g	■ Carbon monoxide[a]	0.07 g
		■ Heavy fuel oil[a]	6.0 g	■ Cardboard waste	15.2 g
	“Use 2″	■ Diesel[a]	0.14 g	■ Carbon monoxide[a]	0,40 g
		■ Exhaust valves	161.2 g	■ Carbon dioxide[b]	5,4E+04 kg
		■ Gasoline[b]	1.7E+04 kg	■ Carbon monoxide[a]	9,0E-04 g
				■ Sulphur dioxide (SO_2)[b]	2,5 kg
				■ Used exhaust valves	161,2 g
Post-use	Recycling	■ Diesel[a]	0.31 g	■ Carbon dioxide[a]	0.8 g
		■ Used exhaust valves	161.2 g	■ Carbon monoxide[a]	2.0E-03 g
				■ Used exhaust valves	161.2 g

[a] Air emissions of CO_2 and CO due to consumption of diesel and heavy fuel oil in transportation activities.
[b] Air emissions of CO_2 and SO_2 due to consumption of gasoline.

treatments (e.g., tempering).

The head machining processes, presented by Fig. 7, include head turning, seat coating, seat grinding, and neck and chamfer grinding. Head turning defines the valve seat. The seat coating operation consists of applying a chemical powder via plasma welding. This chemical powder enhances the valve's sealing ability during its use in the motor vehicle. The remaining operations consist of grinding the valve's head, neck, and chamfer regions. These grinding operations are performed using aluminum oxide or CBN (cubic boron nitride) wheels, and mineral oil as cutting fluid.

Finally, Fig. 8 shows the last set of operations from the finishing and packaging line. It consists of engine valves cleaning, stem polishing with a sanding sheet, and valve packaging using carboard boxes. After that, packaging of engine valves are sent to the engine vehicle manufacturers, and the selected valve model is a product type that is mainly exported to United States.

2.3. Life cycle inventory analysis (LCI)

This second LCA step consists of gathering quantitative inputs and outputs data for each of phases defined by the product system (Fig. 3). The LCI data was obtained from primary and secondary sources. Primary data were collected at the engine valves manufacturing level, based on the data collection methods described by Table 2.

Table 5 presents the direct inventory flows for all life cycle phases to produce the reference flow of four exhaust valves (176.4 g – with packaging). Among the processes within the manufacturing phase, stem and head machining are ones with higher demand for electricity, lubricants and grinding wheel consumptions. Considering the remaining life cycle phases, “Use 2” demanded a significant amount of gasoline fuel, required to perform the passenger vehicle 300,000 km drive defined by the functional unit (Table 4). Regarding the secondary data, some datasets were extracted from LCA databases and literature, as described in Table 6.

Most of the datasets presented in Table 6 were extracted from the GaBi 6.5 LCA software tool (Thinkstep, 2015). Part of these secondary data represents conditions from Brazil, while the remaining portion come from foreign countries (i.e., Europe), due to the unavailability of some Brazilian datasets. The LCI data related to supply chains indirect flows underwent a LCA cut off criteria of 90.0% (mass basis). Indirect flows from the construction of

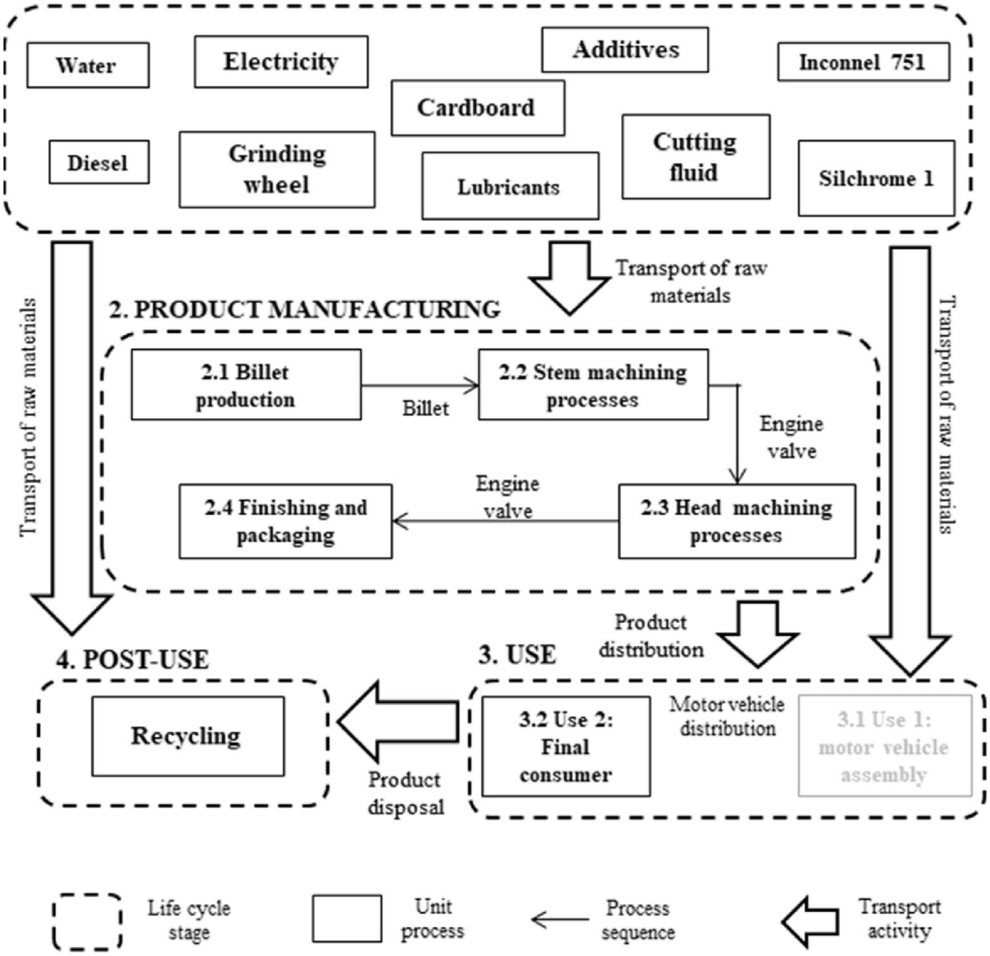

Fig. 3. The LCA case study product system.

machinery were not considered in the scope of the product system and, so, were not included on this study.

Lastly, Table 7 shows distances assumed for transportation of raw materials and for product distribution. The process "GLO: Container ship ELCD/PE-Gabi", available at GaBi 6.5 was used to represent maritime transportation activities (for distances higher than 1000 km), while "GLO: Truck PE, Euro 3, 12.0 t payload", was used to represent the terrestrial logistics systems (for distances up to 1000 km).

2.4. *Life Cycle Impact Assessment (LCIA) and interpretation of results*

The LCIA was performed using the ILCD/PEF recommendation v.1.06 method (EC/JRC/IES, 2010) with attributional approach. Thirteen midpoint impact categories were evaluated: Acidification, accumulated exceedance (AC), Ecotoxicity for aquatic freshwater (EAF), Freshwater eutrophication (FE), IPCC global warming, incl. biogenic carbon (GW), Ionizing radiation (IR), Marine eutrophication (ME), Resource Depletion, fossil and mineral (RD), Ozone depletion (OD), Particulate matter/respiratory inorganics (PM), Photochemical ozone formation (POF), Terrestrial eutrophication, accumulated exceedance (TE), Human toxicity cancer effects, recommended (HTCE), and Human toxicity non-canc. effects, recommended (HTNCE). Most of these categories are in line with prior LCAs of automotive products highlighted in Table 1.

Equation (1) shows how the environmental impact indicators were calculated for each of the selected categories (Reich-Weiser et al., 2013):

$$\mathrm{EI}_k = \sum_k \left(\frac{\sum_s \mathrm{CF}_s \times \mathrm{E}_s}{\mathrm{R}_k} \right). \tag{1}$$

Where:

- $\mathbf{EI}_k$ = environmental impact indicator of category k (e.g., GW, OD, POF, TE, HTCE, etc.);
- $\mathbf{CF}_s$ = characterization factor of environmental aspect s (material consumption, emission to air, water, etc.);
- $\mathbf{E}_s$ = amount of a monitored environmental aspect s;
- $\mathbf{R}_k$ = normalization value of impact category k.

The R_k factors are used to normalize the characterized impact category values in order to support decision-analytic requirements to be met in the normalization step of LCA (Cururachi et al., 2017). CF_s and R_k factors are direct dependent of the selected impact assessment method.

The LCIA results were normalized per person equivalent, following the directives of Environmental Footprint Pilot Guidance from the European Commission (European Commission, 2016), available at GaBi 6.5 software tool as "PEF Pilot, incl. biogenic carbon [Person equivalent]".

The next section presents the LCIA results of the case study

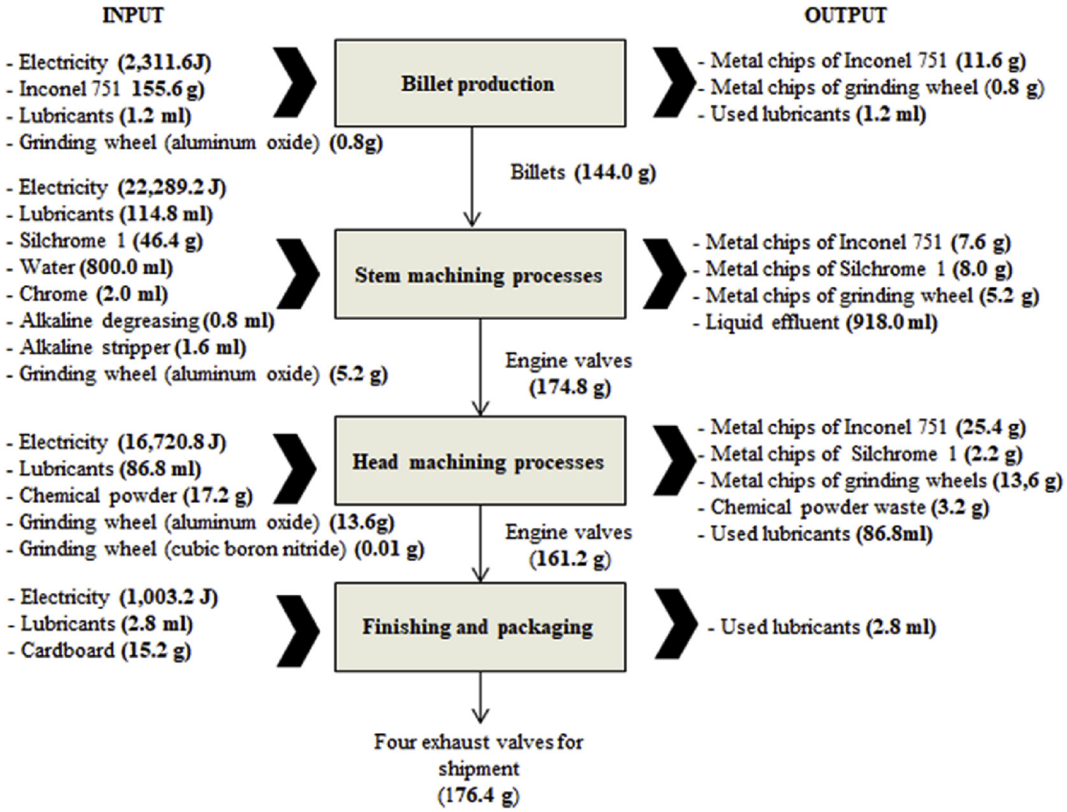

Fig. 4. Exhaust valve manufacturing flowchart.

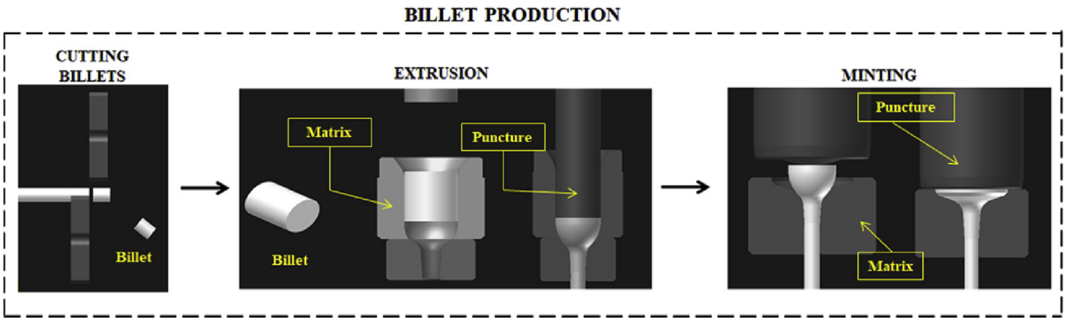

Fig. 5. Disaggregated flowchart of the billet production process.

along with an environmental hotspot analysis.

3. LCA results and environmental hotspot analysis

From the LCI data provided by Table 5, it was possible calculate the LCIA results (see Appendix 2) for the thirteen selected impact categories using GaBi 6.5 software (Fig. 9):

According to the results in Fig. 9 and 79.6% of the normalized impacts occurred for HTCE (33.0%), PM (19.5%), HTNCE (14.1%), and GW (13.0%) categories. For all the evaluated categories, most of the impacts comes from "Use 2" due to its massive amount of gasoline consumption (i.e., 1.7E+04 kg).

The environmental hotspots identified in "Use 2" were related to the atmospheric emissions of carbon monoxide (CO), carbon dioxide (CO_2), sulfur dioxide (SO_2), particulate matter and heavy metals, along with emissions of heavy metals to freshwater. Both emissions to air and to water are derived from the gasoline fuel supply chain and/or the gasoline fuel burning in the internal combustion engines of a passenger vehicle.

Air emissions of CO and CO_2 from the operation of the motor vehicle were calculated based on the GaBi 6.5 process "DE: consumption automotive part" – assuming 60% working in urban areas, and an average performance of 13 km/l. Air and water emissions from the gasoline fuel supply chain are mainly related to the extraction and processing of crude oil (fossil).

The predominance of the use phase on the environmental impact results makes the studied exhaust valves to be considered part of a group of products classified by Aurich et al. (2013) as "Low embodied energy, high energy usage".

The LCIA results also reinforce the finding in the literature. Dornfeld (2014) states that most part of impacts in the use phase of motor vehicles are associated with fuel consumption and, Warsen and Krinke (2013) emphasizes that the potential impacts from the use stage of a vehicle often outweigh the impacts from its

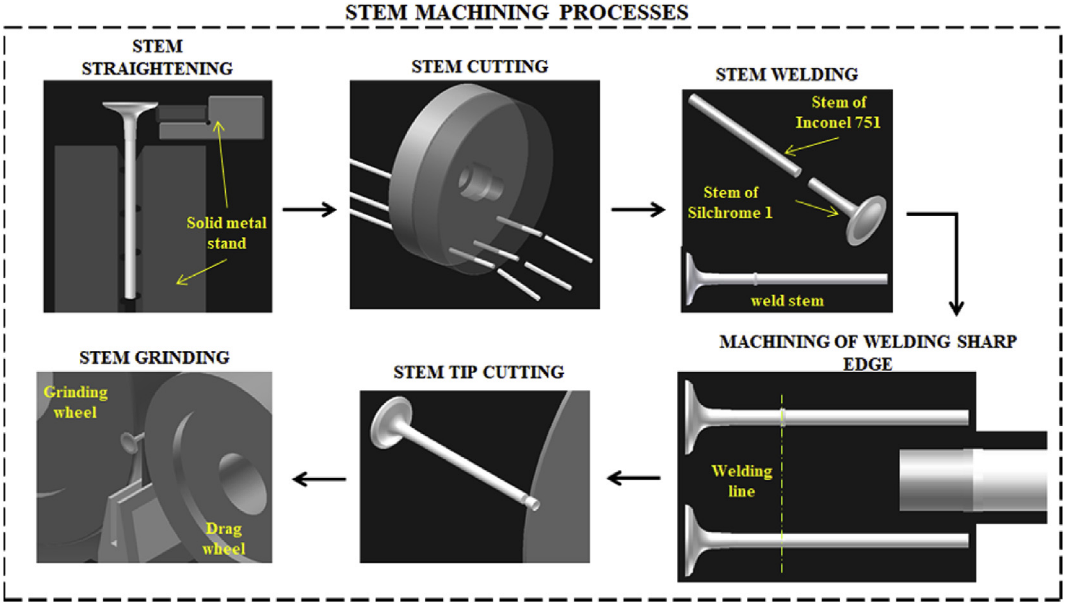

Fig. 6. Disaggregated flowchart of the stem machining processes.

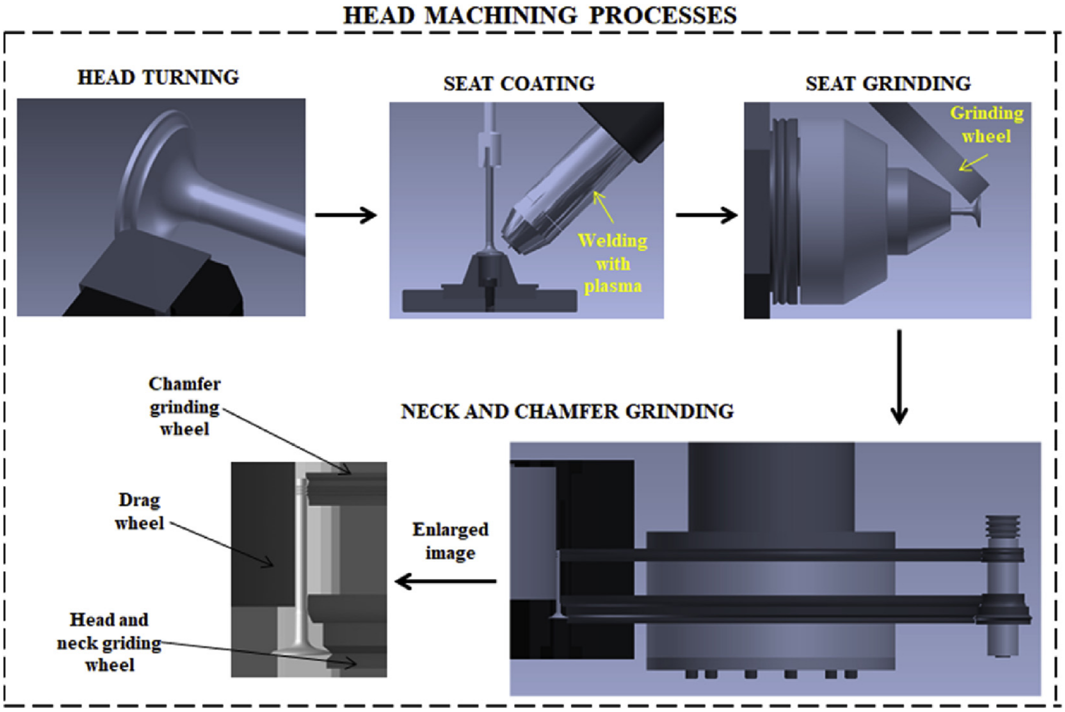

Fig. 7. Disaggregated flowchart of the head machining processes.

manufacturing phase.

In order to have a better understanding regarding the impacts from the other life cycles phases of the exhaust valves, a different LCIA was performed, excluding the impacts from gasoline consumption from “Use 2” (Fig. 10).

In this new scenario, manufacturing is the most impactful phase (~90% of all impacts) and RD and HTNCE were the most relevant impact categories. RD impacts reflect depletion of abiotic resources (fossil and minerals) due to human activities, while HTNCE impacts are related to non-cancer toxic effects from human exposure to environmental pollution (air and water emissions).

Nevertheless, it is worth mentioning that “Use 1” and “Use 2” were modeled in a simplified way, accounting only for the impacts related to the transportation of raw material and distribution of products based on data from Table 7. Post-use impacts due to the recycling process of the engine valves were also insignificant compared to the manufacturing impacts for all the thirteen impact categories, and this result is in line with some prior literature on the topic (Dhingra and Das, 2014). Impacts due to recycling process have accounted for −0.08% of all the normalized impacts.

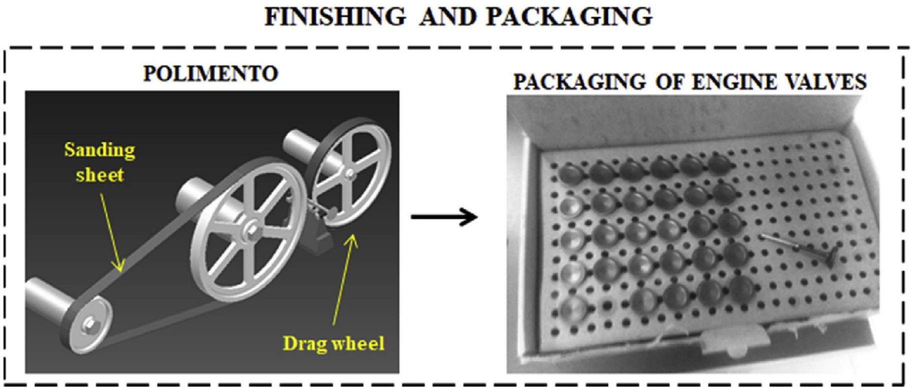

Fig. 8. Disaggregated flowchart of the finishing and packaging processes.

Table 6
Datasets used as background sources for LCI step.

Description	Data source	Nation
Supply of tap water	Thinkstep (2015)	Europe
Supply chain of aluminum, cast iron, manganese, silicon, steel rebar, and sulfur (basic materials and elements to produce Inconel 751 and Silchrome 1)	Thinkstep (2015)	Brazil/Europe
Supply chain of diesel (at refinery)	Thinkstep (2015)	Brazil
Supply chain of electricity grid mix	Thinkstep (2015)	Brazil
Supply chain of gasoline (at refinery)	Thinkstep (2015)	Brazil
Supply chain of cardboard	Thinkstep (2015)	Europe
Supply chain of heavy fuel oil (at refinery)	Thinkstep (2015)	Brazil
Supply chain of grinding wheel (aluminum oxide)	Filleti (2015); Filleti et al. (2017)	Europe
Supply chain of grinding wheel (CBN)	Filleti (2015); Filleti et al. (2017)	Europe
Treatment of metal scrap, post-consumer, prepared for recycling (at remelter)	Thinkstep (2015)	Europe

Fig. 11 shows a stratified view of environmental impacts from the manufacturing phase.

As can be noticed, the stem machining processes were the main environmental hotspot, representing 63% of impact results, followed by the billet production (21%) and the head machining processes (16%). These impacts were mostly related to the electric energy consumption in machining processes, followed by the consumption of Inconel 751, Silchrome 1 and cutting fluids. From these results, cleaner production scenarios were developed in order to address these environmental hotspots.

4. Cleaner production scenarios to reduce environmental impacts in exhaust valve manufacturing

Based on the results provided by the LCI (Fig. 4 and Table 5) and LCIA (Figs. 10 and 11), it was possible to identify some cleaner production practices for the manufacturing phase:

- **Increase resources efficiency in manufacturing phase:** each exhaust valve weights 44.1 g (with packaging), and more than 90% of its physical content are represented by Inconel 751 and Silchrome 1. Thus, it is important to improve resources efficiency for these materials at machining operations of the valve's stem and head. Head machining (turning operation) and stem machining (centerless grinding) generate a great amount of chips from both alloys (Fig. 4). In this line, enhancing resource efficiency at turning and centerless grinding operations may represent a valuable cleaner production alternative;
- **Minimize cutting fluid consumption in the stem and head machining processes:** most of cutting fluid consumption is

Table 7
Distances for transportation of inputs and product distribution.

Input	Departure from	Distance to the engine valve manufacturer (km)
Chrome	São Paulo, Brazil	12.0
Alkaline stripper	São Paulo, Brazil	12.0
Alkaline degreasing	São Paulo, Brazil	12.0
Diesel	São Paulo, Brazil	60.0
Inconel 751	São Paulo, Brazil	150.0
Lubricants	Rio de Janeiro, Brazil	450.0
Heavy fuel oil	São Paulo, Brazil	60.0
Cardboard boxes	São Paulo, Brazil	10.0
Chemical powder	Germany	10,126.0
	Rio de Janeiro, Brazil	450.0
Silchrome 1	São Paulo, Brazil	150.0
Product's distribution activities	**Departure from**	**Distance to the destination (km)**
Distribution of exhaust valves to the motor vehicle producer	São Paulo, Brazil	450.0 km
	United States	10,000.0 km
Distribution of the motor vehicle to the final consumer	United States	100.0 km
Distribution of the used exhaust valves for recycling, at remelter	United States	100.0 km

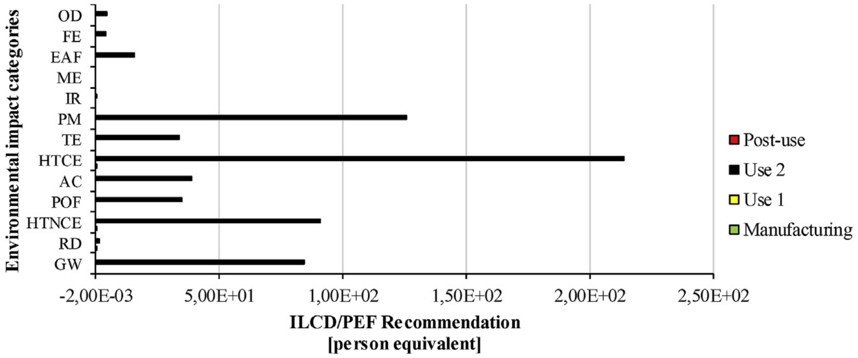

Fig. 9. Case study LCIA results – impacts in person equivalent, ILCD/PEF recommendation v.1.06 method.

associated with the stem machining processes (i.e., 114.8 ml - Fig. 4), especially at the centerless grinding operation. Thus, alternatives to minimize consumption of cutting fluid would be desired;

- **Minimize electricity consumption at stem and head machining processes:** From Fig. 4, it is possible to verify that the consumption of electricity was a hotspot for both stem and head machining. Part of this consumption is related to high-energy demanding of finishing processes, such as grinding. In this vein, a power mapping study for this type of machining operation would be a valuable support to identify ways of reducing electricity consumption.

In section 4.1 it is performed a deeper evaluation of cleaner production scenarios for the centerless grinding operation of the valve's stem. To this end, it was designed an environmental assessment and monitoring system for the centerless grinding process.

4.1. Environmental assessment and monitoring for a centerless grinding process

Due to time and human resources limitations, the evaluation of the centerless grinding was not performed directly in the exhaust valve producer. Instead, the experiments and simulations were designed and carried out in the Laboratory of Advanced Processes and Sustainability (LAPRAS) of the Department of Production Engineering from the São Carlos School of Engineering (EESC), University of São Paulo (USP), Brazil.

The grinding machine used for the experiments was a cylindrical centerless machine tool μicroma brand, Model N1E 0480, year 1998, with 220 V three-phase electrical supply and equipped with aluminum oxide wheels (Fig. 12). Mineral oil (0.87 g/cm^3) was used as cutting fluid with application rate varying from 18 to 36 L/min (Table 8).

This grinding machine was chosen because of its operational similarity with the grinding machines used by the exhaust valve producer. In this way, and based on the collected data from the company representatives, it was possible to simulate the centerless grinding operation of the valve steam with the grinding machine sited at LAPRAS-EESC-USP.

During the centerless grinding simulations, electricity consumption and the cutting fluid consumption were monitored. Electricity consumption (in kJ) was obtained with the aid of a power measurement device and a digital timer. The power device used was a portable power quality analyzer, model ANALYST 3Q CE EO 0600G, produced by LEM, with 0.1 W resolution. This equipment was installed on the electric panel of the machine and performed the collection of electrical current (in A) and voltage data (in V). Using both electrical current and voltage data, the power device is able the machine power demand (in W).

For each machine operation mode (see details in Table 8), operation time (in seconds) was measured using the digital timer. Finally, the consumption of electricity was calculated by integrating the power demand by the operation time for each analyzed operation mode (Table 8).

The cutting fluid consumption was estimated from to the fluid flowrate set for each of the conditions given by Table 8:

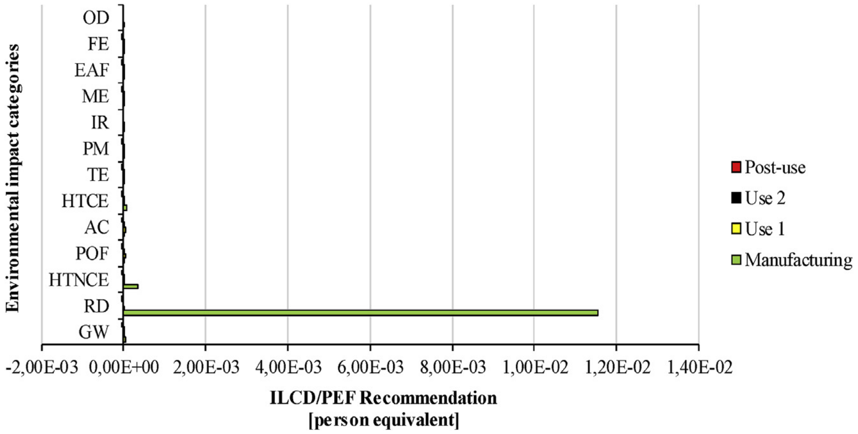

Fig. 10. Case study LCIA results, excluding "Use 2" impacts related to the gasoline consumption – impacts in person equivalent, ILCD/PEF recommendation v.1.06 method.

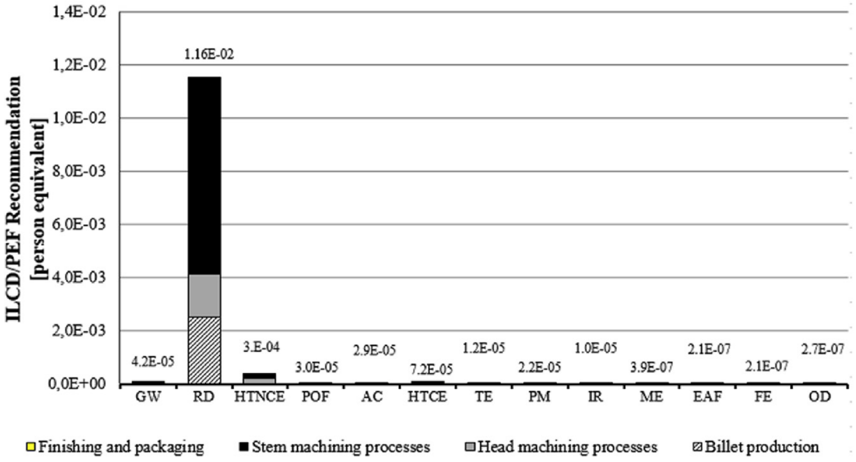

Fig. 11. Disaggregated LCIA results per manufacturing process – impacts in person equivalent, ILCD/PEF recommendation v.1.06 method.

The process parameters presented by Table 8 were defined from the information provided by the company representatives during the survey application (Appendix 1). A scenario analysis in Fig. 13 shows the normalized environmental impacts associated with the production of four exhaust valves (reference flow) for different grinding machine setups and two different cleaner production strategies:

- **Scenario 1:** reduction of cutting fluid consumption in the stand-by and dressing modes. Fluid consumption was set to zero during stand-by, and the consumption in the dressing mode was equal to the same setup value for grinding. Before setting Scenario 1, the grinding process used to consume 36 L/min in both dressing and stand-by modes, as there was no concern for reducing cutting fluid consumption in idle time;

Description of the machine tool subunits and components:

1 – Electrical panel
2 – Hydraulic unit
3 – Dressers speed controller
4 – Machine on/off button
5 – Drag wheel dresser
6 – Feed speed controller of drag wheel
7 – Transverse movement controller of drag wheel
8 – Cutting depth controller in grinding
9 – Grinding wheel, ruler guide and drag wheel
10 – Grinding wheel dresser
11 – Cutting fluid flow rate manual controller

Fig. 12. Overview of the centerless grinding machine sited at LAPRAS-EESC-USP.

Table 8
Process parameters on centerless grinding for the environmental monitoring and assessment.

Description	Unit	Parameters	
Number of passes on dressing (N)	–	4	6
Cutting fluid flow rate on grinding (CF)	L/min	18	36
Machine operation modes	–	Initiation Stand-by Dressing Grinding Turn-off	

- **Scenario 2:** reduction by 50.0% of stand-by mode duration before and after grinding. Stand-by lasts up to 30s according to the valves producer. So, reductions on this idle time could be a good initiative to improve machine productivity as well as for the environmental performance.

Scenarios analysis showed there is a potential impact reduction up to 72% in the stand-by grinding mode, up to 44% in the dressing mode, and up to 21% in the grinding mode if the manufacturing condition N = 4; CF = 18/min - combined with scenarios 1 and 2 is selected. Fig. 13 highlights also that most of impacts are due to stand-by and grinding operation modes, mainly as the result of high energy demand from cutting grinding wheel and hydraulic sub-units activation.

Finally, Fig. 14 provides a cradle-to-grave comparison between the environmental profiles before and after adopting the proposed cleaner production measures. The baseline ("before case") used the LCIA results excluding the gasoline consumption in "Use 2" (Fig. 10) and the case for comparison ("after case") used the same LCIA results, however, changing the impacts from manufacturing phase through the cleaner production scenario of the centerless grinding process under condition N = 4 and CF = 18 L/min, combined with strategies 1 and 2 (Fig. 13). As can be verified, the changes applied for the "after case" resulted in a significant reduction (~27%) on the RD impacts, and consequently, in an improvement of the product life cycle environmental profile.

5. Conclusions

The use of LCA is a relevant tool towards cleaner production of the automotive industry. A case study was used on this paper to investigate cleaner production alternatives based on LCA of engine valves produced in Brazil.

Different exhaust valve models were tested, and the most

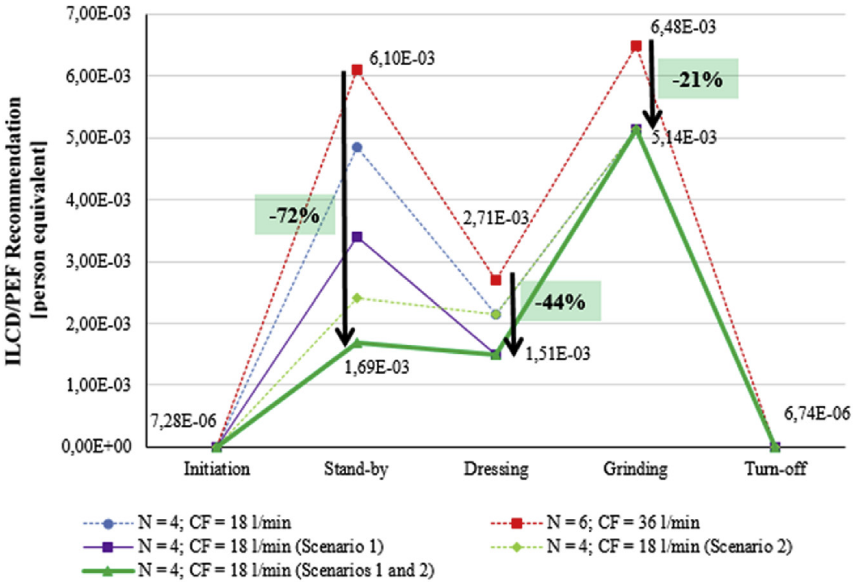

Fig. 13. Environmental assessment of centerless grinding process by means of scenario analysis – impacts in person equivalent, ILCD/PEF recommendation v.1.06 method.

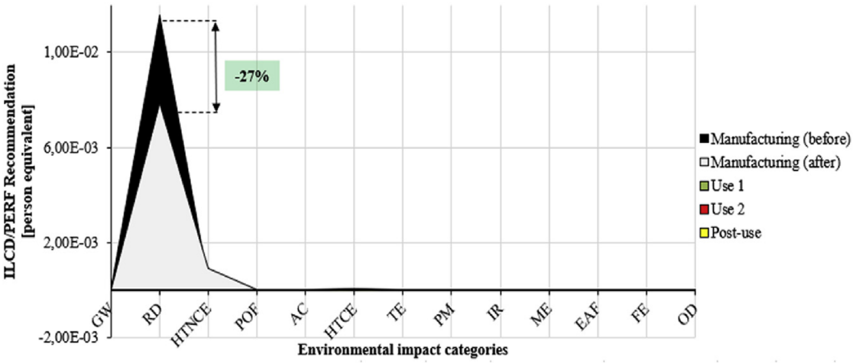

Fig. 14. Environmental profiles (before vs. after cleaner production measures) of exhaust valves, excluding gasoline consumption in "Use 2" - impacts in person equivalent, ILCD/PEF recommendation v.1.06 method.

relevant product was model Nº 3 (exhaust valves for four-wheeled vehicles; gasoline; valves made of chrome-silicon steel and superalloy). The product selection was performed with the Brazilian company's representatives based on results of a questionnaire application available on Appendix 1. The engine valve chosen for the case study represents 40% of the manufacturer market share and it is consumed manly by external markets from United States.

LCIA was performed based on the ILCD/PEF recommendation v.1.06 method (EC/JRC/IES, 2010) and its thirteen midpoint impact categories and normalization factors, by application of Equation (1) and the use of GaBi 6.5 software tool. Results showed that the major part (more than 90%) of all environmental impacts were due to the use phase of the exhaust valves. The consumption of gasoline fuel in motor vehicles was the most impactful environmental aspect for the cradle-to-grave life cycle of exhaust valves. Such conclusion is in accordance with prior studies on the topic (Aurich et al., 2013; Dornfeld, 2014; Helu et al., 2011; Warsen and Krinke, 2013).

However, Figs. 10 and 11 stated that manufacturing processes of the exhaust valves model can be also relevant into the product life cycle if the fuel consumption in the use phase is disregarded. Improving manufacturing processes efficiency may have a direct influence on savings for use phase impact dominant products. The use phase of a motor vehicle involves also dozens of different component parts with different weights and manufacturing processes and materials, and a next step of this research should consider first defining a motor vehicle model to be assembled with and without the exhaust valves under investigation.

On this case study, cleaner production alternatives were proposed based on two scenarios on the stem centerless grinding operation to increase its manufacturing capability yield and saving resources as well (electricity, cutting fluid, raw materials). Section 4.1 showed results of a set of simulations at the centerless grinding process of the valve stem to increase its manufacturing resource efficiency in terms of N and CF parameters for five different operation modes. Further research should also investigate the valve's head machining processes too.

Scenario analysis showed a potential impact reduction up to 72% in the stand-by grinding mode followed by 44% less impacts in the dressing mode for the manufacturing condition $N = 4$; $CF = 18$ l/min - combined with scenarios 1 and 2. Such simple changes on grinding parameters can produce a great minimization of environmental burdens in manufacturing of exhaust valves. In a cradle-to-grave life cycle perspective, these results were compared with previous LCA results on Fig. 10, and it was found an improvement up to 27% on saving RD impacts. Therefore, improve manufacturing parameters can generate a better environmental life cycle performance towards cleaner production.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2018.02.252.

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