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ORIGINAL ARTICLE

Environmental assessment of the automotive cage's production process by life cycle assessment methodology

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Abstract

This study evaluated potential environmental impacts and sought to identify hotspots of the manufacturing processes of an automotive cage used in a constant velocity joint. The objective was to identify which step in the manufacture of cages contributed the most impact. The scope of the analysis consisted of cradle-to-gate and included all steps in the manufacturing process, raw materials, supplies, and logistical data. The functional unit considered was of a single cage (mass of 0.15032 kg). Potential environmental impacts were evaluated with a midpoint scope and an attributional approach for impact categories of global warming—GWP 100a, Ozone depletion, acidification, human toxicity, and resources—with the EDIP 97 method. Results identified that potential environmental impacts were concentrated in transportation; when transportation factors were removed from the analysis, the environmental impact of the consumption of raw materials and gains from recycling of metallic waste were prevalent. In conclusion, the assessment of potential environmental impacts in the manufacture of automotive cages has provided data for environmental assessment studies in the automotive industry and contributed to studies in companies with similar manufacturing processes. This study could be used in future studies comparing automotive components with similar processes and, as such, provide secondary data. The primary data used in this study was obtained from direct measurements from a supplier of 70% of the parts used in the Brazilian domestic market in 2018, and the results demonstrated the potential applications of the SimaPro Classroom software in academia, despite its limitations.

Keywords Life cycle assessment · Life cycle inventory · Metal-mechanic industry · Automotive industry · Vehicle component

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1 Introduction

The automotive parts sector is a fundamental segment in the manufacturing chain of the automobile industry. This segment has a global reach and increasing quality and innovation requirements, which accounts for a significant portion of technology developed in the automobile industry and jobs [1]. In 2022, this sector has projected gross revenues of US$ 35 billion split between automobile manufacturers (61.4%), aftermarket part suppliers (21.7%), exports (13.8%), and intra-industry applications (3.1%). In Brazil, this segment accounts for approximately 243,000 jobs with 61.4% of its expenditure in the acquisition of raw materials [2].

Environmental conservation and possible impacts associated with the manufacture and use of industrialized products have become a growing concern. In order to better understand their environmental role and impact, manufacturers have started to apply life cycle assessment (LCA) to analyze the sustainability potential of their processes and products [3, 4]. An LCA can be applied both to the development of new products or to optimize existing processes, allowing a reduction in environmental impacts and identifying factors affecting environmental performance. In this sense, an LCA can provide the necessary data for environmental resource management systems. An LCA can also be used by the manufacturer to obtain Environmental Product Declaration (EPD) certifications, which discloses environmentally relevant information about the products [5–7].

Standardized LCA procedures were codified by the Associação Brasileira de Normas Técnicas (ABNT) in standards NBR ISO 14040 and NBR ISO 14044 [5, 8]. More recently, post-2010, the LCA was further strengthened through the Programa Brasileiro de Avaliação do Ciclo de Vida – PBACV and the inclusion of LCA in the Política Nacional de Resíduos Sólidos, Lei Federal 12305/2010. This law established shared responsibility in the development of processes and products [9, 10].

Warsen and Krinke [11] noted that the greatest challenges in the automotive sector were climate change, air quality/health, and the sustainable use of resources. In addition, the minimization of environmental impacts must be present over the entire life cycle of the product. Consequently, the impact of all components and materials of new vehicles must be evaluated from initial conception and planning, through the manufacturing process, life use, and recycling.

This paper aims to evaluate environmental issues related to the manufacturing processes of an automotive cage present in a constant velocity joint (CV joint) and to highlight the environmental gain of the steel recycling process. The primary data gathering, used for the study, was conducted in loco at a metalwork plant specialized in driveshaft manufacturing and followed procedures recommended by standards ABNT NBR ISO 14040 and ABNT NBR 14044 [5, 8].

1.1 Review of previous studies

Warsen and Krinke [11] pointed out that an automotive LCA would require data for thousands of parts involving their supply chain and related pre-production processes. Additionally, the multitude of automobile parts, subcomponents, and materials were produced in markedly different processes—each one with its share of energy use, raw material consumption, supplies, and other factors. In particular and related to automotive parts or vehicle production, the authors studied a Volkswagen model manufactured in Germany with a cradle-to-grave analysis. The analysis detailed energy consumption, emissions, and other direct environmental impacts from vehicle manufacture and related processes. The functional unit (FU) for the analysis was a single vehicle with a lifetime of 150,000 km. Data for an LCI was obtained from Volkswagen slim LCI—a procedure for streamlined inventory modeling within life cycle assessment (LCA) of vehicles. They conducted a cradle-to-grave study of a Volkswagen vehicle. Potential environmental impacts in the manufacturing stage were identified in the production and shaping of steel which corresponded to 20 to 60% of all impacts (acidification potential, eutrophication, global warming potential, and photochemical ozone formation potential).

Li et al. [12] conducted a cradle-to-grave LCA of diesel motors manufactured in China. The study sought to qualitatively and quantitatively determine the environmental impact of the lifecycle of a newly produced diesel motor in China. The scope covered from raw material extraction, production of supplies, logistics, component manufacture, lifetime use, and end-of-life disposal. The FU was defined as a diesel engine WD615-87 with 300,000 km of use. Data for the study were obtained from the CLCD (Chinese Core Life Cycle Database) and evaluated 5 categories: primary energy demand (PED), global warming potential (GWP), photochemical ozone creation potential (POCP), acidification potential (AP), and eutrophication potential (EP). In the manufacturing phase and raw material processing, the AP category had the most contribution with 1.98% and 1.56%, respectively. Transportation of raw materials contributed only a small fraction of total energy use due to short travel distances. In the PED category, end-of-life component reconditioning presented a higher use of energy when compared to recycling since 85.7% of components were directly or indirectly repurposed, leaving only a small proportion of material for recycling.

Murbach Junior [13] conducted an LCA specifically on automotive needle roller bearings. The study included component assembly and parts such as inner ring cage and needles. The assigned FU was of a single item of each component, and data were collected *in loco* at manufacturing plants. The study focused on the manufacture of needle roller bearings with the Ecoindicator 99 method on SimaPro software in order to determine environmental impacts. The study considered the impact categories of fossil fuels, inorganic inhalable substances, climate change, land use, carcinogenic substances, acidification, ecotoxicity, and minerals. Results showed that inner ring manufacture accounted for 67.6% of the potential environmental impact of the bearing, followed by roller needles (32.3%) and plastic cage (0.015%). The manufacture of the inner ring and cage occurred in sequential steps starting with machining of a steel tube, washing, thermal treatment, and polishing (face, internal, and external surfaces). Thermal treatment of the inner ring represented 96.6% of the environmental impact, of which 95.7% were propane combustion belonging to the fossil fuel impact category. Machining, washing, and polishing accounted for 0.71/%, 0.46%, and 1.36% of the environmental impact, respectively. The remaining 0.87% was related to finishing and control processes.

Davidson et al. [14] conducted a cradle-to-grave study on lead-based automotive batteries. The FU consisted of 1 kg of refined lead (99.99%), and data were obtained from the European Life Cycle Database (ELCD) built in Gabi Database and online data from the International Lead Association. Logistical data included scrap metal collection and secondary led ingot manufacturers which supplied the primary plate manufacturer. The LCA was conducted with two systems: (i) a cradle-to-gate system and (ii) a cradle-to-gate + phase use, and was developed on Gabi software with the CML 2001 methodology. Results demonstrated that mining and smelting had the most environmental impact in the production of refined lead in the form of GWP. Mining impacts are derived from fossil fuels used in transportation and energy generation. In the manufacture of batteries, lead production from mining or scrap recycling had a significant contribution between 40 and 80% of environmental impacts.

Lopes Silva et al. [15] developed an LCA of automotive motor valves manufactured in Brazil with a cradle-to-grave scope. The FU was of a single 4-cylinder motor for a passenger car with a lifetime of 300,000 km. The valves were used to seal combustion chambers and control combustion gas extraction. Data for LCI were taken from primary and secondary sources. The logistical product flow considered the main materials needed for manufacture and was obtained from the analysis of standards and internal documents of the manufacturer. Environmental hotspots in the manufacturing process were identified as electricity, raw materials, and cutting fluids. The LCIA was developed on Gabi 6.5 Professional software, with ILCD/PEF rv. 1.06 methodology and attributional approach. Midpoint impact categories selected were acidification (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). Results showed that 90% of environmental impacts occurred post-manufacture and in the use of the valves in gasoline engines due to the estimated lifetime useful life of 300,000 km. The environmental impact of the manufacture of the valves was not expressive but had indirect hotspots related to raw material production and supplies. These were electricity use, raw materials for steel, and cutting fluid. Direct manufacturing factors such as lubricants and solid waste did not produce a significant impact in the evaluation. In the case of the automotive industry, Lopes Silva [16] considered electricity, water, cutting oil, greenhouse atmospheric emissions, and solid industrial waste as the most important flows.

Common to these studies, regardless of the automotive component or its composition (be it metal or polymer), was that the FU consisted of a single unit coupled or not to a lifetime of use. Regarding data, a variety of sources were considered. Primary data were taken directly from manufacturing processes while secondary data were taken from databases, especially those related to raw materials and industrialized supplies produced prior to the manufacture of the FU [12, 13, 15]. Shipping of raw materials and supplies made use of representative data from the supply chain and accounted for the location of suppliers, manufacturers, and assembly plants [12, 15]. In general, the studies reviewed adopted a cradle-to-grave scope [11, 12, 14, 15]. The midpoint impact categories most evaluated in automotive parts were acidification potential, eutrophication potential, global warming potential, and photochemical ozone creation potential [11, 12, 14, 15]. However, Li et al. and Davidson et al. also considered primary energy demand to evaluate electricity generation and use in the processes [12, 14]. No specific prevalent software or methodology was used. Warsen and Krinke and Li et al. made use of software and methodologies specific to a process or region [11, 12], while Davidson et al. and Lopes Silva et al. made use of the Gabbi software [14, 15] and Murbach Junior used SimaPro [13]. The LCIA methodology also varied between studies: CML 2001 [14], Ecoindicator 99 [13], and ILCD/PEF [15].

2 Methodology

This study presents a case study carried out in partnership with a metalwork manufacturer, an automotive driveshaft manufacturer, in the state of Rio Grande do Sul, Brazil. The LCA procedures were in accordance with Brazilian standards NBR ISO 14040 and NBR ISO 14044 [5, 8] and encompassed all the steps provided for in an LCA study (step 1, definition of objective and scope; step 2, life cycle inventory (LCI); step 3, evaluation of life cycle—LCIA; and step 4, interpretation of results). For the construction of the inventory (step 2), primary data were used, obtained in on-site visits to the manufacturer.

2.1 Description of case studies

The cage is a component of a constant velocity joint (CV joint), responsible for constantly transmitting the force (torque) from the engine to the wheels. The cage houses ball bearings responsible for the transfer of torque from the fixed part of the driveshaft while allowing free wheel movement as seen in Fig. 1. The cage is coupled to the driveshaft by the fixed joint and can also be present or not in a plunging joint.

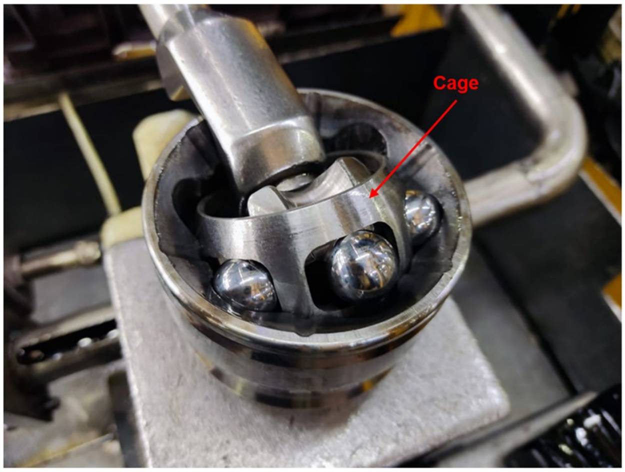


Fig. 1 Automotive cage housing ball bearings—part of a constant velocity joint (CV joint)—which transfers torque from the motor to the drive wheels

The partnered business with an average monthly production of 27,000 parts of automotive driveshaft, of which 70% are for the domestic market and 30% exported. The cage applied to fixed or plunging joints is produced from AISI 8617H Ni–Cr-Mo steel supplied from a steel mill in the state of Minas Gerais, Brazil.

The scope of this study was cradle-to-gate, in which "cradle" corresponding to the extraction and processing of raw materials and supplies used in the cage and "gate" was the actual manufacturing process.

The production system for the driveshaft is shown in Fig. 2 with the relevant steps marked in red. The data quality for this study was evaluated through the Pedigree matrix [17].

In order to define a functional unit (FU) for this study, Table 1 presents data regarding the number of cages present in vehicles based on traction system (front or rear-wheel drive).

Table 2 shows the function, functional unit, and the respective reference flow of the evaluated product system. Since the quantity of cages in a single vehicle varied depending on the type of traction system and CV joint, the FU was defined as a single cage production with a mass of 0.15032 kg.

2.2 Life cycle inventory (LCI)

As set in standards, the life cycle inventory (LCI) is a data-gathering stage with procedures to determine and quantify inflows and outflows in a life cycle [8]. The LCI aims to identify and assess all environmental loads or elementary flows generated by a product or activity throughout its life cycle, allowing the identification of real or potential harmful environmental effects. Thus, an LCI evaluated raw materials consumption, atmospheric emissions, effluents, solid waste, etc. [18].

Fig. 2 Description of product system and boundaries. System boundaries are shown in red (from supplier to the finished product. This includes all steps in the manufacturing chain, raw materials and supplies, and shipping data from suppliers to the manufacturing plant)

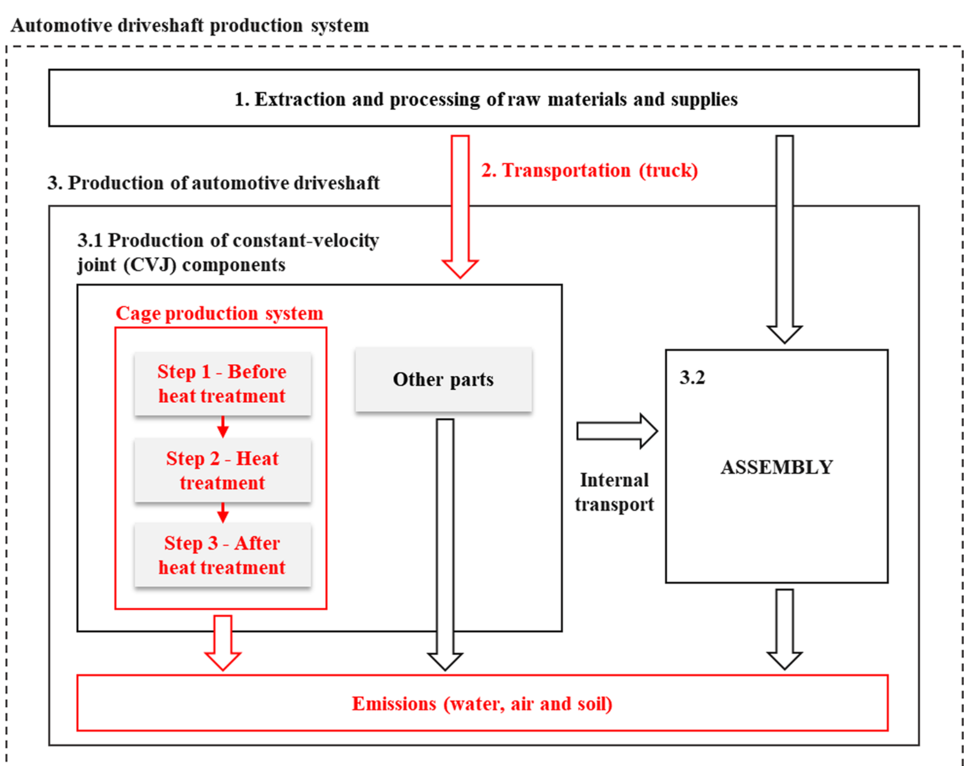


Table 1 Number of cages per CV joint

Drive type	Number of driveshafts	Composition of each driveshaft	Placement	Part used to house ball bearings
Front	2	1 fixed joint	Wheel	1 cage
		1 plunging joint	Gearbox	1 cage or 1 tripod
Rear	2	2 plunging joints	Wheel	1 cage or 1 tripod
			Gearbox	1 cage or 1 tripod

Table 2 Definitions of product, function, functional unit (FU), and reference flow of this study

Product	Automotive cage used in fixed and plunging CV joints
Function	To house ball bearings that transfer torque and allow free wheel movement with the driveshaft
Functional unit	Single cage
Reference flow	Production of a single cage from AISI 8617H, Ni–Cr-Mo steel alloy with a final mass of 0.15032 kg

Data acquisition for inventory compiling was conducted in qualitative and quantitative analyses. The qualitative analysis provided a systemic overview of all operations involved in cage manufacturing, raw materials consumption, and waste generated at each step of the process. This was performed with *in loco* activities which allowed interaction with the processes and workers. Data collected were used as a foundation of a process flowchart and aided in the follow-up quantitative primary data acquisition. The quantitative analysis consisted of data gathering from direct observations to compile the inventory. Primary inflow and outflow data (raw materials, supplies, energy, shipping, solid waste, atmospheric emissions, and effluents) were determined with respect to the designated FU of a single cage. Results were reviewed within the study group, and data gathering was repeated as needed for verification purposes.

The cage manufacturing process consisted of 14 distinct operations grouped in 3 steps:

- Step 1: Occurred before heat treatment and contained machining processes (cutting, shaping, turning, stamping, and internal polishing and broaching). This step produced the shape of the part with the removal of excess steel-generating residues such as swarfs, chips, and shavings. Oils such as cutting fluids, lubricating oils, coolants, and hydraulic fluids were also consumed.
- Step 2: Comprised of heat treatment with controlled application of heating and cooling on the steel to improve its mechanical properties for subsequent operations of the manufacturing process. This step contained processes of washing, carburizing, quenching, tempering, and blasting with steel shot. Mill scale or oxidation of the parts was not examined in this study but, if occurring, would require cleaning by blasting with steel abrasives. Heat treatment processes consumed an elevated amount of water and resulted in effluents that were treated in an in-site effluent treatment plant (ETP). The ETP consumed fuel (methanol and propane) and generated sludge which was not examined in this study.
- Step 3: Occurred after heat treatment and consisted of grinding processes. These included outer grinding with emulsifiable oil filter, inner grinding and window grinding with integral oil filter, tumbling, and machine oiling. These processes resulted in a polished and better-finished part once its surface mechanical properties were set.

The average monthly production of 643,417 cages in the time period of data collection (May and August of 2018) was used to determine the consumption of raw materials and supplies, waste generation, and electricity consumption. Results were converted into kg in accordance to the density of raw materials and supplies (when applicable) obtained from Fichas de Informação e Segurança de Produtos Químicos (FISPQs). Electricity consumption was determined from the kWh rating of the equipment in accordance to the designed FU. Solid wastes were measured with a Toledo scale model 2180 3T9 / IIC, available in situ, with a maximum capacity of 2500 kg, minimum capacity of 12.5 kg, and precision of ± 500 g.

Electrical energy consumption was evaluated from the baseline power consumption of the equipment used in the production process of cages. Data was initially listed in kVA and converted to kW. A conversion factor of 1.0 kVA = 0.9 kW was suggested by the maintenance supervisor at the partnered business due to the variety of equipment used in the manufacturing process. However, since equipment did not operate at 100% throughout an 8-h shift, a 65% or 0.65 conversion factor was chosen as the demand factor (DF).

The heat treatment process was not exclusive of the cages. In reality, two additional components (designated A and B) were treated alongside the cages. For the quantifications related to this process, it was necessary to carry out a mass allocation; thus, it was observed that the cages corresponded to 33.44% of the production of this stage. The full data set is shown in Table 3.

Shipping of raw materials and supplies was purely through truck freight from suppliers to the manufacturing plant. Data relative to the FU were obtained from invoices and shipping manifests of dangerous products and converted into kg.km. Shipping distances were determined from Google Maps. Atmospheric emissions in gCO_2 were calculated from software SimaPro Classroom 8.0 and Ecoinvent

Table 3 Amount and type of part heat treated between May and June of 2018

Part	Period—2018				Total (4 months)	Monthly average	Percent production
	May	Jun	Jul	Aug			
Cage	646,485	588,280	624,490	686,320	2,545,575	636,394	33.44
A	612,140	1,080,110	1,030,350	987,160	3,709,760	927,440	48.73
B	352,648	305,950	335,600	362,820	1,357,018	339,255	17.83
Total	1,611,273	1,974,340	1,990,440	2,036,300	7,612,353	1,903,088	100
Total A + cage	1,258,625	1,668,390	1,654,840	1,673,480	6,255,335	1,563,834	82.17

dataset (Transport, freight, lorry 16–32 metric ton, EURO4) with the EDIP/97 method. It should be noted that shipping of residue for treatment or recycling was not included in the scope of this study.

2.3 Life-cycle impact assessment (LCIA): methodology and limitations

The life-cycle impact assessment (LCIA) was performed using data obtained from the inventory, constructed with primary data acquired through direct measurements. According to Marmiroli et al. [19], LCA studies need more primary data, less aggregated, and presented in a transparent way. The data obtained were modeled in the SimaPro 8.0.1 Classroom software, which uses the data from Ecoinvent 3.0.1 and does not allow for uncertainty analysis using the Monte Carlo method.

For software data entry, some supply data were not present in Ecoinvent 3.0.1 and were replaced with similar products. For example, hydraulic, consumable, emulsifiable, straight, coolant, and quenching oils were all designated as lubricating oil. This procedure was taken from Lopes Silva et al. [15] with acknowledgment that it would induce a level of uncertainty in the results. Lubricating oils could be synthetic or conventional as well as petroleum-based or not. Regardless of the type, lubricating oils possessed high viscosity and long aliphatic and aromatic hydrocarbon chains making them suitable for automotive, industrial, and other applications. About 80 to 90% of lubricating oils are composed of a base oil with 5 to 20% of additives such as anticorrosives, antioxidants, dispersants, detergents, and viscosity modulators [20].

The evaluation of potential environmental impacts was conducted with a midpoint scope, attributional approach, and impact categories of global warming—GWP 100a (g CO_2), ozone depletion (g CFC11), acidification (g SO_2), human toxicity air (m^3), human toxicity water (m^3), human toxicity soil (m^3), and resources—all (kg). The EDIP 97 methodology was used, which, among the impact assessment methods available in the SimaPro 8.0.1 Classroom software, was considered by the authors to be the method with the widest range of impact categories because it has global applicability. For such a decision, the authors used a survey carried out by Mendes N.C [21], which listed the main methods, which categories are contemplated, and the applicability. A recycling factor of 100% was applied to match the business partner's actions.

3 Results and discussion

3.1 Life cycle inventory (LCI)

The data acquired allowed a qualitative analysis of inflow (raw and processed materials) and outflow (solid waste, atmospheric emissions, and effluents) and were used to assemble the manufacturing process flowchart shown in Fig. 3. The flowchart contains 14 distinct operations grouped in 3 steps: before heat treatment, heat treatment, and after heat treatment.

Inventory inflows and outflows obtained from acquired data are shown in Tables 4, 5, and 6, which correspond to step 1, before heat treatment; step 2, heat treatment; and step 3, after heat treatment and inventory shipping of supplies and raw materials, respectively.

In order to gain a better understanding of the contribution of each raw material/supply inflow, solid waste, atmospheric emissions, and effluent outflows, a relative contribution (%) analysis was performed. This analysis allowed the identification of hotspots at each step, marked in bold in Tables 4, 5, and 6. A cutoff mass value of 1% was adopted for inflows and outflows so that their added contribution would not exceed 2%.

In Table 4, step 1, before heat treatment hotspots, was the inflow of raw materials (steel tube) with an 83.62% contribution and emulsifiable (mineral) oil with a 14.39% contribution. These two inflows resulted in 98% of the total inflow mass with remaining inflows contributing 2%. Outflow hotspots were related to metallic residues due to the substantial removal of material in machining processes. The main outflow contributions were from metal chips with oil waste (30.77%), stamping metal with oil waste (26.85%),

Fig. 3 Process flowchart for the manufacturing process of cages. It consists of 14 distinct operations grouped into 3 stages: before heat treatment, heat treatment, and after heat treatment: (A) part covered in quenching oil and (B) part washed and cleaned

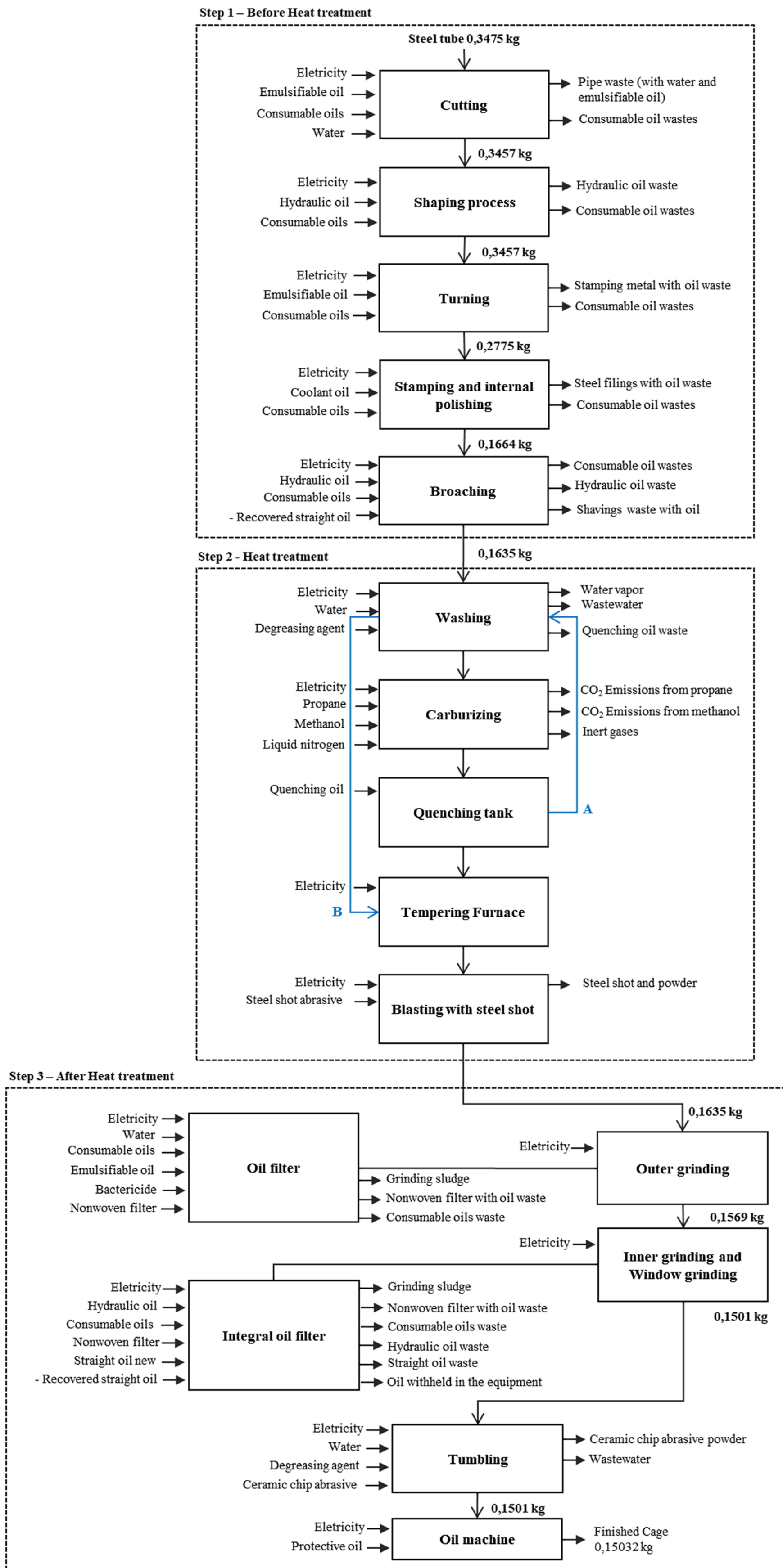


Table 4 Step 1 inventory: before heat treatment (cutting, shaping process, turning, stamping, and internal polishing and broaching)

Description	Flow	Average amount	Unit	Contribution (%)	Compartment	Pedigree
Steel tube AISI 8617H	Input	3.48E-01	kg	83.62%	Technosphere (materials)	(2, 4, 2, 1, 1)
Eletricity	Input	4.84E-01	kWh	-	Technosphere (electricity)	(1, 4, 2, 1, 1)
Water	Input	2.25E-03	kg	0.54%	Technosphere (materials)	(2, 4, 2, 1, 1)
Emulsifiable oil	Input	5.98E-02	kg	14.39%	Technosphere (materials)	(2, 4, 2, 1, 1)
Consumable oils	Input	2.98E-03	kg	0.72%	Technosphere (materials)	(2, 4, 2, 1, 1)
Hydraulic oil	Input	8.96E-04	kg	0.22%	Technosphere (materials)	(2, 4, 2, 1, 1)
Coolant oil	Input	5.38E-04	kg	0.13%	Technosphere (materials)	(2, 4, 2, 1, 1)
Recovered straight oil	Input	1.63E-03	kg	0.39%	Technosphere (materials)	(2, 4, 2, 1, 1)
Consumable oils waste	Output	2.98E-03	kg	0.72%	Technosphere (waste and emissions for treatment)	(2, 4, 2, 1, 1)
Hydraulic oil waste	Output	8.96E-04	kg	0.22%	Technosphere (waste and emissions for treatment)	(2, 4, 2, 1, 1)
Pipe waste (with water and emulsifiable oil)	Output	4.11E-03	kg	0.99%	Technosphere (waste and emissions for treatment)	(2, 4, 2, 1, 1)
Metal chips with oil waste	Output	1.28E-01	kg	30.77%	Technosphere (waste and emissions for treatment)	(2, 4, 2, 1, 1)
Stamping metal with oil waste	Output	1.12E-01	kg	26.85%	Technosphere (waste and emissions for treatment)	(2, 4, 2, 1, 1)
Steel filings with oil waste	Output	4.62E-03	kg	1.11%	Technosphere (waste and emissions for treatment)	(2, 4, 2, 1, 1)
Oil withheld in the equipment	Output	9.87E-05	kg	0.02%	Internal recycling	(2, 4, 2, 1, 1)
Product step 1	Output	1.64E-01	kg	39.32%	Technosphere—product	(2, 4, 2, 1, 1)

Table 5 Step 2 inventory: heat treatment (washing, carburizing, quenching tank, tempering furnace, and blasting with steel shot)

Description	Flow	Average amount	Unit	Contribution (%)	Compartment	Pedigree
Product step 1	Input	1.64E-01	kg	75.02%	Technosphere (materials)	(2, 4, 2, 1, 1)
Electricity	Input	4.16E-01	kWh	-	Technosphere (electricity)	(1, 4, 2, 1, 1)
Water	Input	2.66E-02	kg	12.22%	Technosphere (materials)	(2, 4, 2, 1, 1)
Degreasing agent	Input	7.83E-04	kg	0.36%	Technosphere (materials)	(2, 4, 2, 1, 1)
Propane	Input	1.07E-02	kg	4.92%	Technosphere (materials)	(2, 4, 2, 1, 1)
Methanol	Input	1.42E-02	kg	6.50%	Technosphere (materials)	(2, 4, 2, 1, 1)
Liquid nitrogen	Input	4.92E-06	kg	0.00%	Technosphere (materials)	(2, 4, 2, 1, 1)
Quenching oil	Input	1.73E-03	kg	0.80%	Technosphere (materials)	(2, 4, 2, 1, 1)
Steel shot abrasive	Input	3.84E-04	kg	0.18%	Technosphere (materials)	(2, 4, 2, 1, 1)
Water vapor	Output	6.84E-04	kg	0.31%	Emissions to air	(2, 4, 2, 1, 1)
Wastewater	Output	2.67E-02	kg	12.21%	Technosphere (waste and emissions for treatment)	(2, 4, 2, 1, 1)
Quenching oil waste	Output	1.73E-03	kg	0.79%	Technosphere (waste and emissions for treatment)	(2, 4, 2, 1, 1)
CO_2 emissions from propane	Output	6.52E-03	kg	2.98%	Emissions to air	(4, 4, 2, 1, 1)
CO_2 emissions from methanol	Output	1.94E-02	kg	8.87%	Emissions to air	(4, 4, 2, 1, 1)
Liquid nitrogen	Output	4.92E-06	kg	0.00%	Emissions to air	(4, 4, 2, 1, 1)
Steel shot and powder	Output	3.84E-04	kg	0.18%	Technosphere (waste and emissions for treatment)	(2, 4, 2, 1, 1)
Product step 2	Output	1.64E-01	kg	74.66%	Technosphere—Product	(2, 4, 2, 1, 1)

and steel filings with oil waste (1.11%). In total, metallic residues amounted to 58.73% of the outflow mass while the remaining forms of waste added up to 1.95%.

In Table 5, step 2, heat treatment inflow hotspots, was water used for washing the parts (12.22%), methanol (6.50%), and propane (4.92%). These amounted to a total

Table 6 Step 3 inventory: after heat treatment (outer grinding + emulsifiable oil filter, inner grinding and window grinding + integral oil filter, tumbling, and oil machine)

Description	Flow	Average amount	Unit	Contribution (%)	Compartment	Pedigree
Product step 2	Input	1.64E-01	kg	79.52%	Technosphere (materials)	(2, 4, 2, 1, 1)
Electricity	Input	8.17E-01	kg	-	Technosphere (electricity)	(1, 4, 2, 1, 1)
Water	Input	1.16E-02	kg	5.62%	Technosphere (materials)	(2, 4, 2, 1, 1)
Emulsifiable oil	Input	2.14E-03	kg	1.04%	Technosphere (materials)	(2, 4, 2, 1, 1)
Consumable oils	Input	1.78E-03	kg	0.87%	Technosphere (materials)	(2, 4, 2, 1, 1)
Hydraulic oil	Input	8.95E-03	kg	4.35%	Technosphere (materials)	(2, 4, 2, 1, 1)
New straight oil	Input	4.93E-03	kg	2.40%	Technosphere (materials)	(2, 4, 2, 1, 1)
Bactericide	Input	1.58E-04	kg	0.08%	Technosphere (materials)	(2, 4, 2, 1, 1)
Nonwoven filter	Input	9.77E-04	kg	0.48%	Technosphere (materials)	(2, 4, 2, 1, 1)
Recovered straight oil	Input	1.11E-02	kg	5.40%	Technosphere (materials)	(2, 4, 2, 1, 1)
Ceramic chip abrasive	Input	1.17E-04	kg	0.06%	Technosphere (materials)	(2, 4, 2, 1, 1)
Degreasing agent	Input	1.66E-04	kg	0.08%	Technosphere (materials)	(2, 4, 2, 1, 1)
Protective oil	Input	2.21E-04	kg	0.11%	Technosphere (materials)	(2, 4, 2, 1, 1)
Grinding sludge	Output	2.17E-02	kg	10.55%	Technosphere (waste and emissions for treatment)	(2, 4, 2, 1, 1)
Nonwoven filter with oil waste	Output	2.39E-03	kg	1.16%	Technosphere (waste and emissions for treatment)	(2, 4, 2, 1, 1)
Consumable oils waste	Output	1.78E-03	kg	0.87%	Technosphere (waste and emissions for treatment)	(2, 4, 2, 1, 1)
Hydraulic oil waste	Output	8.95E-03	kg	4.35%	Technosphere (waste and emissions for treatment)	(2, 4, 2, 1, 1)
Straight oil waste	Output	9.41E-03	kg	4.58%	Technosphere (waste and emissions for treatment)	(2, 4, 2, 1, 1)
Oil withheld in the equipment	Output	9.68E-03	kg	4.71%	Internal recycling	(3, 4, 2, 1, 1)
Ceramic chip abrasive powder	Output	1.17E-04	kg	0.06%	Technosphere (waste and emissions for treatment)	(2, 4, 2, 1, 1)
Wastewater	Output	1.25E-03	kg	0.61%	Technosphere (waste and emissions for treatment)	(2, 4, 2, 1, 1)
Finished cage	Output	1.50E-01	kg	73.11%	Technosphere—product	(2, 4, 2, 1, 1)

inflow mass of 23.64% with the remaining inflows contributing 1.33%. Outflow hotspots were directly related to the inflows: wastewater (12.21%) and CO_2 emissions from the combustion of methane (8.87%) and propane (2.98%). These added up to a 24.06% total outflow mass while the remaining outflows added up to 1.28%.

In Table 6, step 3, after heat treatment inflow hotspots, was identified as water and emulsifiable oil used in the grinders (5.62%), hydraulic oil (4.35%), new straight oil (2.4%), emulsifiable oil (1.04%), and recovered straight oil (5.4%). These amounted to a total inflow mass of 18.81%. It should be noted that recovered straight oil was repurposed within the manufacturing plant and part of it was used in the grinders and further recovered. The remaining inflows added up to a contribution of 1.66%. Outflow hotspots were identified as grinding sludge (10.55%), oil withheld in the equipment (4.71%), straight oil waste later recovered (4.58%), hydraulic oil waste (4.35%), and nonwoven filter waste (1.16%). These wastes accounted for 25.36% of the outflow mass while remaining residues amounted to 1.53%.

Results of this study were similar to those of Murbach Junior for the manufacturing process of the inner ring of a needle roller bearing [13]. Like the cage of this study, the manufacturing process of the inner ring consisted of several sequential steps starting from machining a steel tube, washing, heat treatment, and internal, external, and surface grinding. In the machining step, the main inflow hotspots were the steel tube supply, electrical energy, and emulsifiable cutting oil, while the outflow hotspots were swarfs from the cutting process. It should be noted that cutting oil was applied in a closed circuit and, as such, was not considered an outflow. In the washing process, the main hotspots were water consumption, residues, and effluent sent to the ETP. The heat treatment step consisted of carburization, quenching, and normalization, and its main inflow hotspots were identified as electrical energy, nitrogen gas, liquid fuel (propane and methanol), and quenching oil. In this case, quenching oil was assumed to be used in a closed system, and CO_2 emissions from propane and methanol were not evaluated. In the grinding step, the main inflow hotspots were identified as electrical energy consumption and water + emulsifiable oil mixture, while outflow hotspots were sludge from emulsions and metallic powder from polishing.

3.2 Life-cycle impact assessment (LCIA)

The manufacturing process of the automotive cage consisted of 3 steps (before heat treatment, heat treatment, and after heat treatment). Consequently, the evaluation of potential environmental impacts was modeled at each step.

3.2.1 Step 1: before heat treatment

The step 1, before heat treatment, consisted of machining processes: cutting, shaping, turning, stamping, internal polishing, and broaching. In Fig. 4, as demonstrated, the potential environmental impacts were concentrated in the transportation of supplies and raw materials (Ni–Cr-Mo steel), which represented for 99.08% of the inflow in step 1. Steel was transported from out-of-state suppliers over long distances (1684 km) and accounted for the most mass (83.62%) in the process. Road freight transportation impact all production chains since, at some point along its life cycle, all product must utilize road transportation for raw materials and supplies, delivery to clients, or specific logistical services. In Brazil, 64.7% of all loads were transported on roads [22, 23].

To further assess potential environmental impacts, an evaluation of step 1 was conducted without transportation and the results are shown in Fig. 5. Results showed that once transport was removed from consideration, the environmental contribution of the raw material and the environmental gain from recycling metallic waste (negative axis of the graph), with emphasis on the human toxicity air (m^3) impact category.

The contribution analysis (% impact) of step 1 is shown in Fig. 6. The analysis concluded that the transportation of raw materials and supplies affected all impact categories, especially global warming, ozone depletion, and human toxicity (soil and air).

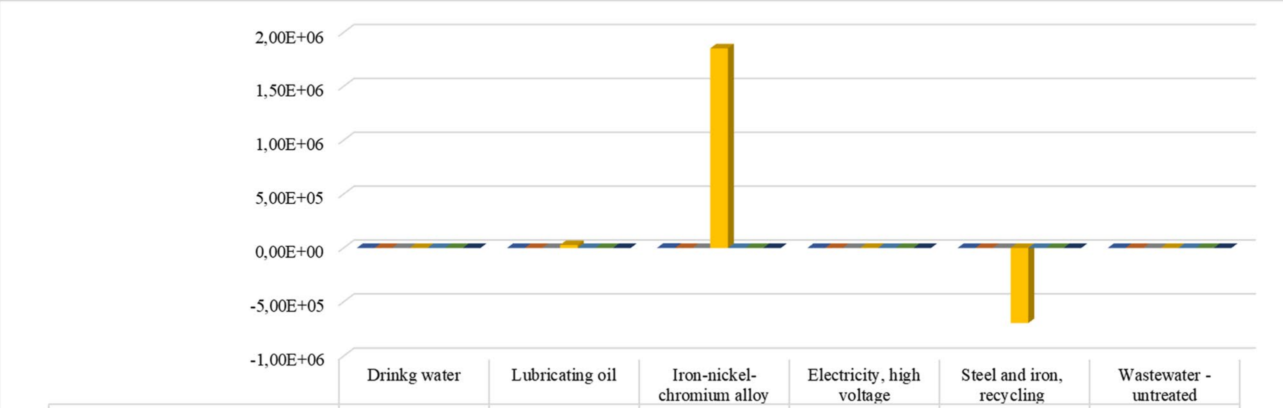
3.2.2 Step 2: heat treatment

Heat treatment consists of controlled heating and cooling of steel to obtain desired mechanical properties for later processes or, in the case of steel, imbue adequate hardness and mechanical strength to the product [24]. A complete assessment of potential environmental impacts is presented in Fig. 7 considering supplies, electricity, transportation, and waste and emissions for treatment. Similar to step 1, potential environmental impacts in step 2 concentrated in the transportation of supplies and human toxicity air category. This was in agreement with Ferreira which identified human toxicity and photochemical ozone formation as impact categories from emissions of road freight transportation. The most negative impacts in these categories were from carbon monoxide (CO) emissions [24].

In contrast, when transportation was excluded from the analysis in Fig. 8, step 2 impacts were identified from methanol and propane used as fuel in heat treatment, electricity, and quenching oil in the human toxicity air (m^3) category. This result differed from Murbach Junior [13] which did not include transportation and identified fossil fuels (propane)

	Drinkg water	Lubricating oil	Iron-nickel-chromium alloy	Electricity, high voltage	Transport of supplies and raw materials	Steel and iron, recycling	Wastewater - untreated
Global warming - GWP 100a (g CO2)	1,30E-03	8,03E+01	1,91E+03	6,30E+00	1,18E+05	-3,98E+02	2,47E+00
Ozone depletion (g CFC11)	1,52E-11	2,29E-05	7,91E-05	1,06E-07	8,04E-03	-1,07E-05	1,39E-08
Acidification (g SO2)	3,15E-06	4,87E-01	3,45E+02	1,55E-02	5,58E+02	-1,47E+00	5,87E-03
Human toxicity air (m³)	4,82E-02	2,73E+04	1,85E+06	1,05E+03	2,63E+07	-6,94E+05	8,46E+01
Human toxicity water (m³)	3,46E-06	3,70E-01	1,00E+02	3,04E-02	3,54E+02	-2,12E+00	5,60E-03
Human toxicity soil (m³)	1,01E-08	2,29E-02	9,58E-01	9,37E-04	2,00E+01	-8,45E-01	1,64E-05
Resources - all (kg)	2,86E-11	1,77E-05	1,65E-02	1,73E-06	1,55E-02	7,33E-06	8,76E-09

Fig. 4 Complete assessment of the potential environmental impacts (supplies and raw material, electricity, transportation, and waste and emissions for treatment) of step 1, before heat treatment



	Drinkg water	Lubricating oil	Iron-nickel-chromium alloy	Electricity, high voltage	Steel and iron, recycling	Wastewater - untreated
Global warming - GWP 100a (g CO2)	1,30E-03	8,03E+01	1,91E+03	6,30E+00	-3,98E+02	2,47E+00
Ozone depletion (g CFC11)	1,52E-11	2,29E-05	7,91E-05	1,06E-07	-1,07E-05	1,39E-08
Acidification (g SO2)	3,15E-06	4,87E-01	3,45E+02	1,55E-02	-1,47E+00	5,87E-03
Human toxicity air (m³)	4,82E-02	2,73E+04	1,85E+06	1,05E+03	-6,94E+05	8,46E+01
Human toxicity water (m³)	3,46E-06	3,70E-01	1,00E+02	3,04E-02	-2,12E+00	5,60E-03
Human toxicity soil (m³)	1,01E-08	2,29E-02	9,58E-01	9,37E-04	-8,45E-01	1,64E-05
Resources - all (kg)	2,86E-11	1,77E-05	1,65E-02	1,73E-06	7,33E-06	8,76E-09

Fig. 5 Assessment of the potential environmental impacts without transportation (supplies and raw material, electricity, and waste and emissions for treatment) of step 1, before heat treatment

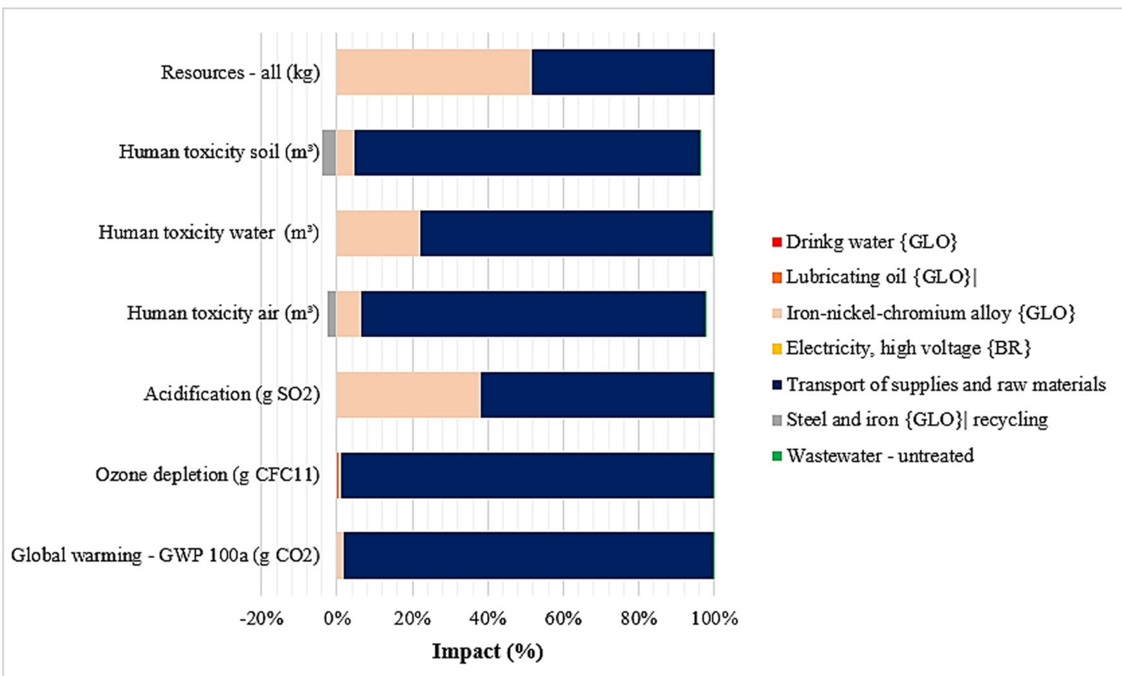


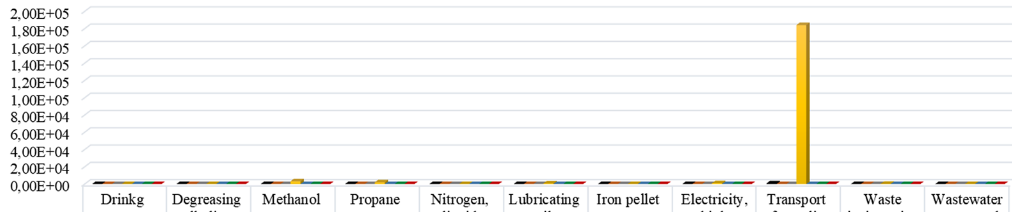
Fig. 6 Contribution analysis (% impact) of step 1, before heat treatment

as the most significant contributing impact factor (95.7%) in the heat treatment of the inner ring.

The contribution analysis (% impact) of step 2 is shown in Fig. 9. Similar to step 1, transportation of supplies contributed across all impact categories.

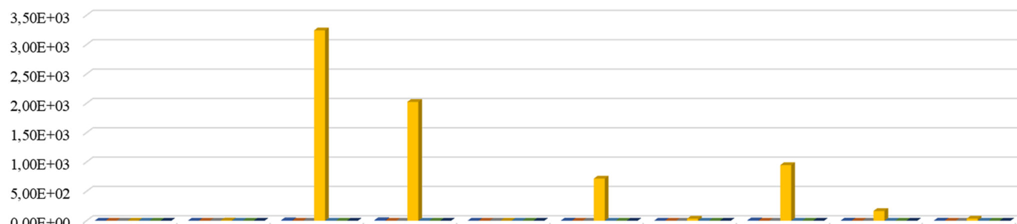
3.2.3 Step 3: after heat treatment

After heat treatment consisted of grinding processes: outer grinding + emulsifiable oil filter, inner grinding and window grinding + integral oil filter, tumbling, and oil machining.



	Drinkg water	Degreasing alkaline	Methanol	Propane	Nitrogen, liquid	Lubricating oil	Iron pellet	Electricity, high voltage	Transport of supplies and raw materials	Waste incineration of ferro metals	Wastewater - untreated
Global warming - GWP 100a (g CO2)	1,54E-02	1,22E-02	8,55E+00	8,98E+00	2,90E-03	2,11E+00	8,22E-02	5,67E+00	8,23E+02	1,08E+00	1,04E+00
Ozone depletion (g CFC11)	1,80E-10	9,55E-10	8,29E-07	2,44E-06	1,09E-10	6,01E-07	6,33E-09	9,55E-08	5,62E-05	9,63E-08	5,85E-09
Acidification (g SO2)	3,73E-05	8,89E-05	9,14E-02	5,17E-02	1,89E-05	1,28E-02	1,09E-03	1,39E-02	3,90E+00	2,50E-03	2,47E-03
Human toxicity air (m³)	5,70E-01	5,12E+00	3,24E+03	2,02E+03	4,39E-01	7,17E+02	3,37E+01	9,47E+02	1,84E+05	1,66E+02	3,57E+01
Human toxicity water (m³)	4,10E-05	2,63E-04	2,55E-02	3,46E-02	8,67E-06	9,73E-03	6,37E-04	2,74E-02	2,47E+00	4,10E-03	2,36E-03
Human toxicity soil (m³)	1,20E-07	7,11E-05	3,55E-03	2,15E-03	3,41E-07	6,01E-04	3,16E-05	8,42E-04	1,40E-01	1,34E-04	6,90E-06
Resources - all (kg)	3,39E-10	4,18E-09	1,39E-06	8,44E-07	1,06E-10	4,65E-07	3,31E-08	1,55E-06	1,08E-04	3,42E-08	3,69E-09

Fig. 7 Complete assessment of the potential environmental impacts (supplies, electricity, transportation, and waste and emissions for treatment) of step 2, heat treatment



	Drinkg water	Degreasing alkaline	Methanol	Propane	Nitrogen, liquid	Lubricating oil	Iron pellet	Electricity, high voltage	Waste incineration of ferro metals	Wastewater - untreated
Global warming - GWP 100a (g CO2)	1,54E-02	1,22E-02	8,55E+00	8,98E+00	2,90E-03	2,11E+00	8,22E-02	5,67E+00	1,08E+00	1,04E+00
Ozone depletion (g CFC11)	1,80E-10	9,55E-10	8,29E-07	2,44E-06	1,09E-10	6,01E-07	6,33E-09	9,55E-08	9,63E-08	5,85E-09
Acidification (g SO2)	3,73E-05	8,89E-05	9,14E-02	5,17E-02	1,89E-05	1,28E-02	1,09E-03	1,39E-02	2,50E-03	2,47E-03
Human toxicity air (m³)	5,70E-01	5,12E+00	3,24E+03	2,02E+03	4,39E-01	7,17E+02	3,37E+01	9,47E+02	1,66E+02	3,57E+01
Human toxicity water (m³)	4,10E-05	2,63E-04	2,55E-02	3,46E-02	8,67E-06	9,73E-03	6,37E-04	2,74E-02	4,10E-03	2,36E-03
Human toxicity soil (m³)	1,20E-07	7,11E-05	3,55E-03	2,15E-03	3,41E-07	6,01E-04	3,16E-05	8,42E-04	1,34E-04	6,90E-06
Resources - all (kg)	3,39E-10	4,18E-09	1,39E-06	8,44E-07	1,06E-10	4,65E-07	3,31E-08	1,55E-06	3,42E-08	3,69E-09

Fig. 8 Assessment of the potential environmental impacts without transportation (supplies, electricity, and waste and emissions for treatment) of step 2, heat treatment

These processes resulted in a final desired visual aspect of the cage.

As in step 1 and step 2, Fig. 10 demonstrates that environmental impacts were concentrated in the transportation of supplies under the human toxicity air (m^3) category.

However, once transportation was excluded from the analysis, Fig. 11 points out the impact of lubricating oils (emulsifiable, consumable, hydraulic, straight, and protective) and non-woven filter with oil. The former represented approximately 9% of inflow supplies while the latter was incinerated (co-processing). An environmental gain was also identified attributed to the recycling of metallic wastes (negative axis of the graph).

The contribution analysis (% impact) of step 3 is shown in Fig. 12. Similar to step 1 and step 2, transportation of supplies contributed to all impact categories.

3.2.4 Comparatives analysis

A comparative contribution analysis (% impact) of the steps in cage manufacture is shown in Fig. 13. Results showed that step 1 (before heat treatment) accounted for approximately 97% of the impacts across all categories. This was likely a result of steel tube AISI 8617H demand which, as noted in Sect. 3.1, represented 83.62% of the inflow mass alongside transportation both of oils and steel. In contrast, steps 2 and 3 contributed 0.6% and 2.4%, respectively.

To analyze the contribution (% impact) of electricity and oils used in the processes (emulsifiable, consumable, hydraulic, coolant, quenching, and straight oil), they were evaluated separately in order to identify the step in which they contributed the most. As shown in Fig. 14, oils had

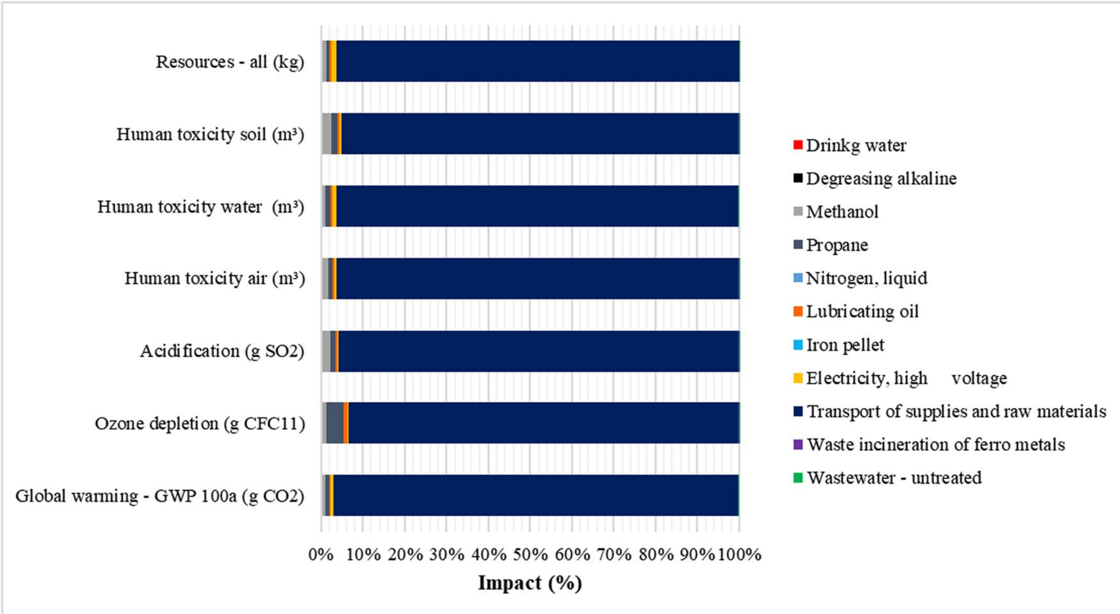
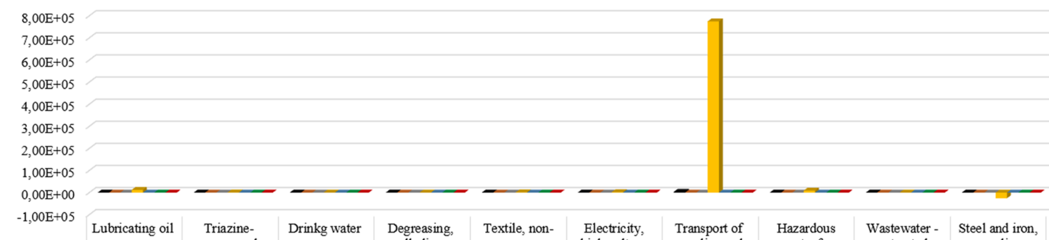


Fig. 9 Contribution analysis (% impact) of step 2, heat treatment



	Lubricating oil	Triazine-compound	Drinkg water	Degreasing, alkaline	Textile, non-woven polyester	Electricity, high voltage	Transport of supplies and raw materials	Hazardous waste, for incineration	Wastewater - untreated	Steel and iron, recycling
Global warmingl - GWP 100a (g CO2)	3,55E+01	1,20E+00	6,70E-03	2,67E-03	4,16E+00	1,09E+01	3,46E+03	5,78E+01	4,42E-01	-1,47E+01
Ozone depletion (g CFC11)	1,01E-05	3,87E-07	7,84E-11	2,08E-10	2,09E-07	1,83E-07	2,36E-04	5,17E-06	2,49E-09	-3,95E-07
Acidification (g SO2)	2,16E-01	6,79E-03	1,62E-05	1,94E-05	1,49E-02	2,67E-02	1,64E+01	1,34E-01	1,05E-03	-5,42E-02
Human toxicity air (m³)	1,21E+04	3,14E+02	2,48E-01	1,12E+00	7,62E+02	1,81E+03	7,75E+05	8,89E+03	1,52E+01	-2,56E+04
Human toxicity water (m³)	1,64E-01	9,68E-03	1,78E-05	5,74E-05	9,17E-03	5,24E-02	1,04E+01	2,20E-01	1,00E-03	-7,80E-02
Human toxicity soil (m³)	1,01E-02	1,91E-04	5,20E-08	1,55E-05	9,98E-04	1,61E-03	5,89E-01	7,16E-03	2,93E-06	-3,11E-02
Resources - all (kg)	7,84E-06	2,37E-07	1,47E-10	9,12E-10	3,92E-07	2,98E-06	4,56E-04	1,83E-06	1,57E-09	2,70E-07

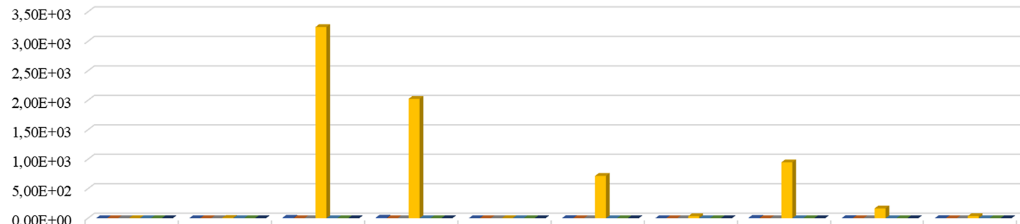
Fig. 10 Complete assessment of the potential environmental impacts (supplies, electricity, transportation, and waste and emissions for treatment) of step 3, after heat treatment

significant contributions on all impact categories and, in particular, in steps 1 and 3.

The contribution analysis for waste and emissions for treatment (percentage of impact (%)) is shown in Fig. 15. Results show environmental gains from recycling metallic waste in global warming (GWP 100a), acidification, human toxicity (air, water, and soil), and ozone depletion impact categories. However, the opposite was determined for category resources, all. This was a result of the high energy consumption required to smelt steel for recycling, use of pig iron complement (75% scrap + 25% pig iron), and alloy elements which depend on the type of steel being produced and furnace [25]. Further potential (negative) environmental impacts were noted in the incineration (co-processing) of hazardous waste and had contributions in all impact categories, with emphasis on the categories ozone depletion, resources (all), and global warming.

4 Conclusions

This study was developed with the aim of carrying out an environmental assessment of the manufacturing process of automotive cages present in CV joints and highlighting the



	Drinkg water	Degreasing alkaline	Methanol	Propane	Nitrogen, liquid	Lubricating oil	Iron pellet	Electricity, high voltage	Waste incineration of ferro metals	Wastewater - untreated
Global warming - GWP 100a (g CO2)	1,54E-02	1,22E-02	8,55E+00	8,98E+00	2,90E-03	2,11E+00	8,22E-02	5,67E+00	1,08E+00	1,04E+00
Ozone depletion (g CFC11)	1,80E-10	9,55E-10	8,29E-07	2,44E-06	1,09E-10	6,01E-07	6,33E-09	9,55E-08	9,63E-08	5,85E-09
Acidification (g SO2)	3,73E-05	8,89E-05	9,14E-02	5,17E-02	1,89E-05	1,28E-02	1,09E-03	1,39E-02	2,50E-03	2,47E-03
Human toxicity air (m³)	5,70E-01	5,12E+00	3,24E+03	2,02E+03	4,39E-01	7,17E+02	3,37E+01	9,47E+02	1,66E+02	3,57E+01
Human toxicity water (m³)	4,10E-05	2,63E-04	2,55E-02	3,46E-02	8,67E-06	9,73E-03	6,37E-04	2,74E-02	4,10E-03	2,36E-03
Human toxicity soil (m³)	1,20E-07	7,11E-05	3,55E-03	2,15E-03	3,41E-07	6,01E-04	3,16E-05	8,42E-04	1,34E-04	6,90E-06
Resources - all (kg)	3,39E-10	4,18E-09	1,39E-06	8,44E-07	1,06E-10	4,65E-07	3,31E-08	1,55E-06	3,42E-08	3,69E-09

Fig. 11 Assessment of the potential environmental impacts without transportation (supplies, electricity, and waste and emissions for treatment) of step 3, after heat treatment

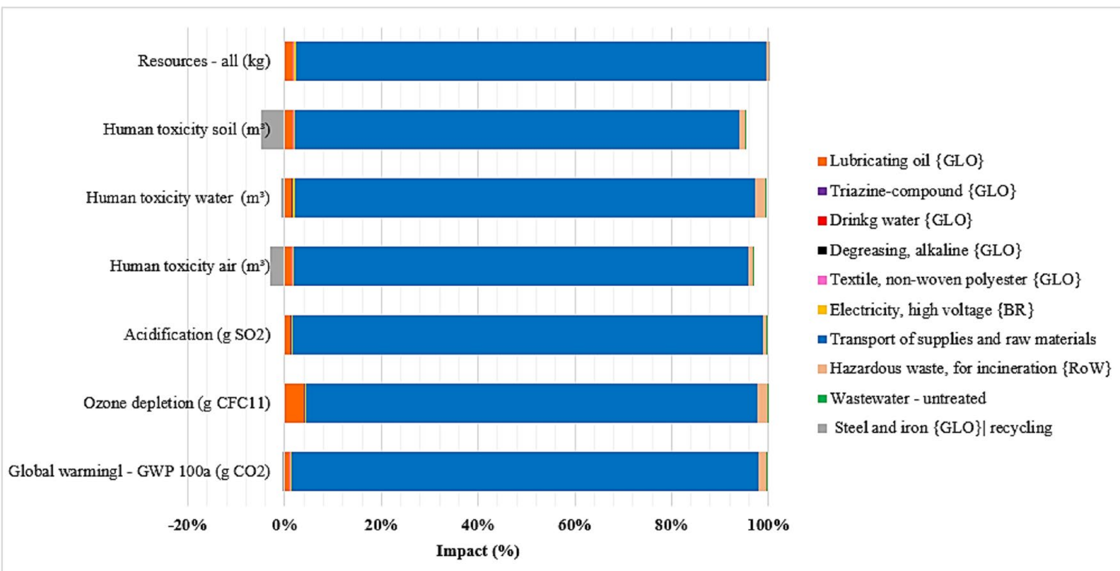
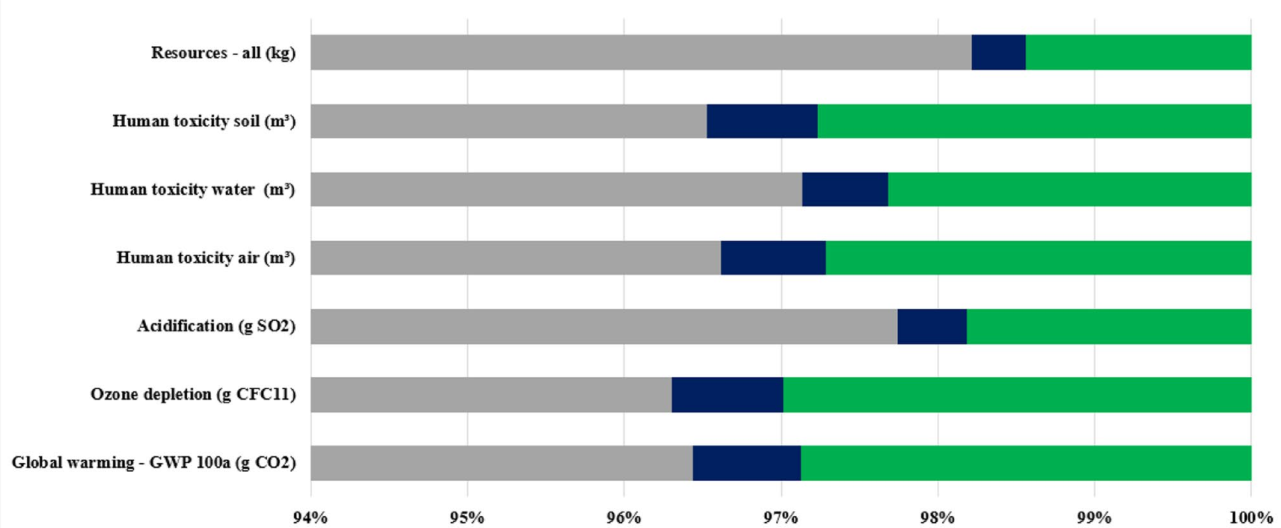


Fig. 12 Contribution analysis (% impact) of step 3, after heat treatment

environmental gain of the steel recycling process. In addition, the study provides primary data on the manufacturing process of one of the components of the CV joint. This data can be used in studies of the automotive segment, as well as in studies of segments that use similar machining, heat treatment, and grinding processes.

A comparison of the three manufacturing stages determined that stage 1 (before heat treatment) was responsible for approximately 97% of the impacts in all the categories selected for this study. This was a result of the demand for raw materials in the form of AISI 8617H steel pipe, which accounted for 83.62% of the input mass in stage 1, and the transportation of steel and oils. A similar result was obtained by Davidson et al. in the manufacture of lead-based automotive batteries, with lead production accounting for most of the impact (> 85%) [14].

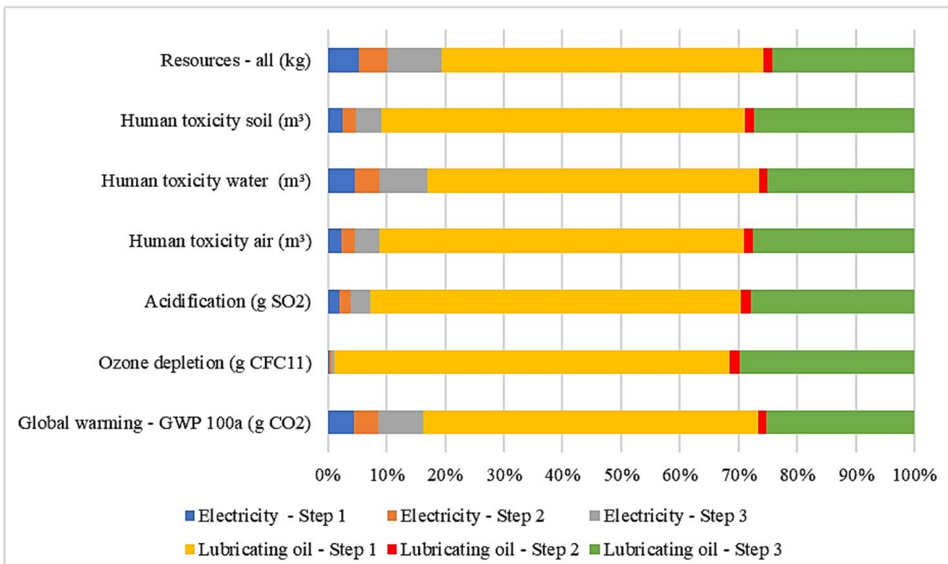
The potential environmental impact of the oils used in the process (emulsifiable, consumable, hydraulic, and pure oil) was more significant than the use of electricity in stages 1 and 3. The contribution analysis (% impact) for waste and emissions for treatment confirmed the environmental gain of recycling metal waste in the impact categories global warming (GWP 100a), acidification, human toxicity (air, water, and soil), and ozone depletion. The analysis also confirmed a (negative) environmental impact from the incineration (co-processing) of hazardous waste, especially in the categories



	Global warming - GWP 100a (g CO2)	Ozone depletion (g CFC11)	Acidification (g SO2)	Human toxicity air (m³)	Human toxicity water (m³)	Human toxicity soil (m³)	Resources - all (kg)
Before heat treatment (total)	96,44 %	96,30 %	97,74 %	96,62 %	97,13 %	96,53 %	98,21 %
Heat treatment (total)	0,69 %	0,71 %	0,44 %	0,67 %	0,55 %	0,71 %	0,35 %
After heat treatment (total)	2,88 %	2,99 %	1,82 %	2,71 %	2,32 %	2,77 %	1,44 %

Fig. 13 Complete contribution analysis of all processes

Fig. 14 Contribution analysis of electricity and oils used in the manufacture of cages (emulsifiable, consumable, hydraulic, and straight oil)



of ozone depletion, resources (all), and global warming. It should be noted that the impact of the consumption of lubricating oils would have been minimized if a re-refining process had been included in the study. It is therefore recommended that lube oil re-refining be added in future analyses.

Logistically, the raw materials and most of the inputs were transported from outside the state over an average distance of 1336 km. Consequently, the results pointed to a significant contribution from the transportation of raw materials and inputs to the potential environmental impacts, since they were calculated based on the load transported and the distance traveled (km). This was observed at all stages of cage production especially in the category of human air toxicity (m^3).

In conclusion, the assessment of potential environmental impacts in the manufacture of automotive cages has provided data for environmental assessment studies in the automotive industry and contributed to studies in companies with

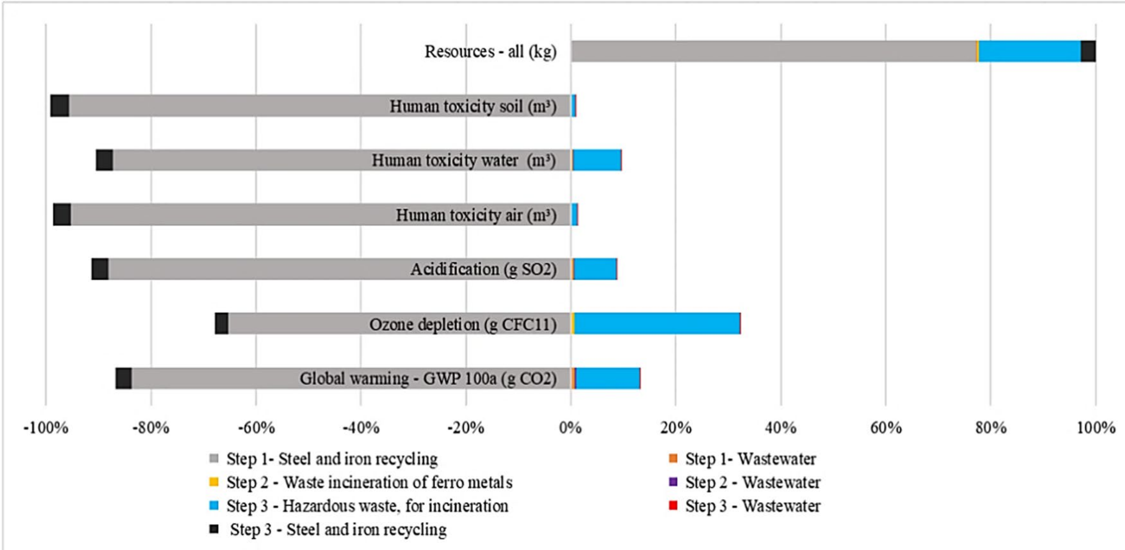


Fig. 15 Contribution analysis (% impact) of waste and emissions for treatment

similar manufacturing processes. This study could be used in future studies comparing automotive components with similar processes and, as such, provide secondary data. The primary data used in this study was obtained from direct measurements from a supplier of 70% of the parts used in the Brazilian domestic market in 2018, and the results demonstrated the potential applications of the SimaPro Classroom software in academia, despite its limitations.

Environmental impacts could be minimized by improving the use of raw materials and inputs, process control, oil consumption, minimizing losses, and increasing recycling within the manufacturing process. With regard to raw materials, the high amount of waste, despite the environmental gains identified in recycling, pointed to the need to minimize the scrap waste generated in the stage 1 machining process and to make more efficient use of steel tubes.

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Author contribution All authors contributed to the conception and design of the study. The life-cycle impact assessment (LCIA) was modeled in the SimaPro 8.0.1 Classroom software by Marilise Garbin, Rafael Batista Zortea, and Feliciane Andrade Brehm. Daniela Hennemann, Viviana Nedel Reckziegel, Fernando Dalvite da Silva, and Francielle Oliveira de Vargas da Silva helped in the primary data collection used in the modeling. The manuscript was written by Marilise Garbin, and the authors Feliciane Andrade Brehm, Rafael Batista Zortea, Carlos Alberto Mendes Moraes, and Regina Célia Espinosa Modolo commented on previous versions of the manuscript. All authors have read and approved the final manuscript.

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Declarations

Conflict of interest The authors declare no competing interests.

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