LIFE CYCLE INVENTORY (LCI) OF A MECHANICAL GEARBOX MANUFACTURING PROCESS

INVENTÁRIO DE CICLO DE VIDA (ICV) DE UM PROCESSO DE FABRICAÇÃO DE CAIXA DE TRANSMISSÃO MECÂNICA

INVENTARIO DEL CICLO DE VIDA (ICV) DE UN PROCESO DE FABRICACIÓN DE UNA CAJA DE TRANSMISIÓN MECÁNICA

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ABSTRACT
The metal-mechanical industry bears an environmental responsibility with respect to the proper use of natural resources. This translates into constant efforts to develop processes and products with optimum use of raw materials, incorporate clean technologies and reduce waste generation. A life cycle assessment (LCA) is an environmental resource management tool that evaluates all stages in the life cycle of a product or process. In this study, a simplified LCA was applied to the manufacturing process of a mechanical gearbox. Primary data from a life cycle inventory (LCI) were used to determine the mass balance of solid metallic waste per functional unit (FU) and energy balance. The energy balance was of 56.96kWh/FU, acquired through free market supply. Thus, the LCI was able identify possible the environmental aspects and impacts which could be used as future guidelines.

KEYWORDS
LCI, block diagram, mechanical gearbox

RESUMO
A indústria metalmecânica possui uma responsabilidade ambiental na utilização dos recursos naturais, estando em constante busca do desenvolvimento dos processos e produtos visando a otimização do uso de matérias-primas, emprego de tecnologias limpas, e a minimização da geração de resíduos. A ACV é uma ferramenta de gestão ambiental que avalia todas as etapas do ciclo de vida de um produto ou processo, e diante deste cenário a pesquisa aplicou a metodologia de ACV simplificada no processo de fabricação de uma caixa de transmissão mecânica. Com os dados primários do ICV foram elaborados o balanço mássico dos resíduos sólidos metálicos por unidade funcional (UF) e o balanço energético. Através dos resultados obtidos foram propostas melhorias através da aplicação de P+L em parte do processo. O balanço energético resultou em 56,96kWh/UF, em que foi utilizada energia de aquisição pelo mercado livre de energia. Com os resultados do ICV foram identificados os possíveis aspectos e impactos ambientais do processo pesquisado, os dados que auxiliam na tomada de decisões futuras.

PALAVRAS-CHAVE
ICV, diagrama de blocos, caixa de transmissão mecânica

RESUMEN
La industria metalmecánica mantiene una responsabilidad ambiental en la utilización de los recursos naturales y busca constantemente desarrollar procesos y productos con vistas a optimizar el uso de materias primas, emplear tecnologías

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limpias y minimizar la generación de residuos. La ACV es una herramienta de gestión ambiental que evalúa todas las etapas del ciclo de vida de un producto o proceso, y ante este escenario, la investigación aplicó la metodología de ACV simplificada en el proceso de fabricación de una caja de transmisión mecánica. A partir de los datos primarios del ICV se elaboró el balance de masa de residuos sólidos metálicos por unidad funcional (UF) y el balance energético. A través de los resultados obtenidos se propusieron mejoras mediante la aplicación de P+L en parte del proceso. El balance energético arrojó 56,96kWh/UF, que utilizó energía adquirida a través del mercado libre de energía. Con los resultados del ICV se identificaron los posibles aspectos e impactos ambientales del proceso investigado, datos que ayudan en la toma de decisiones futuras.

PALABRAS CLAVE
ICV, Diagrama de bloques, Caja de transmisión mecánica

1. INTRODUCTION

The constant evolution of the manufacturing sector and unbounded consumption of natural resources results in environmental, economic and social impacts (Jamwal *et al.*, 2021b; Priarone *et al.*, 2021). Additionally, Industry 4.0 initiatives promote the efficient use of resources and large scale production with automation and smart systems (Jamwal *et al.*, 2021a; Manuguerra *et al.*, 2023). These combined demands bring the need to evaluate manufacturing processes and develop solutions with significant effects on productivity and sustainability (Reis *et al.*, 2023). This has additional consequences since sustainability concerns are a considerable challenge to industry and affects its competitiveness (Siltori, 2020; Vrchota *et al.*, 2020).

The manufacturing sector in the state of Rio Grande do Sul is the 2nd largest in Brazil both in terms of plants and employment (Rio Grande Do Sul, 2021). Consequently, it carries substantial environmental responsibilities in conservation, handling and use of natural resources. This requires the development of processes and products that optimize the consumption of raw materials, applies clean technologies and minimizes waste generation (Potrich; Teixeira; Finotti, 2007). To this end, a life cycle analysis (LCA) is one of the most appropriate methodologies since it encompasses the entire life cycle of a process or product (Guinée *et al.*, 2011). The analysis starts at the extraction and processing of raw materials, followed by manufacturing, packing, transportation, distribution, use, re-cycling or re-use until final destination (Fernandes *et al.*, 2019; Hinz; Valentina; Franco, 2006).

Life cycle concepts have been promoted over the past decades through policies and government agencies (Guinée *et al.*, 2011). Some examples were the National Policy on Solid Wastes (PNRS) which determined shared responsibility on the life cycle of products, Sustainable Public Acquisition Guidelines (GCPS) which promoted labels based on LCA that attest to sustainable products and services and the Brazilian Life Cycle Assessment Program (PBACV) developed jointly by Associação Brasileira de Ciclo de Vida (ABCV), Instituto Brasileiro de Informação em Ciência e Tecnologia (IBICT) and Instituto Nacional de Metrologia, Qualidade e Tecnologia (INMETRO) (Cherubini; Ribeiro, 2015).

An LCA is a complex methodology covered in Brazilian standards NBR ABNT ISO 14040, 14041, 14042 and 14043. It evaluates a production system through inflows and outflows. Inflows are the raw materials and energy consumption of the system while outflows are emissions, wastes, co-products and environmental discharges (Barros *et al.*, 2019). An LCA allows an industrial segment to identify opportunities of improved environmental performance at several stages along the life cycle of\a product. Additional benefits would be positive marketing engagement (Cherubini; Ribeiro, 2015) and project design with realistic sustainable solutions (Selhorst; Alves; Nobre, 2020).

Alvarenga *et al.* (2012) presented a simplified LCA which was less complex than a detailed LCA and did not fully comply with all guidelines from ISO standards. However, this simplified LCA could be applied as qualitative, quantitative or semi-quantitative analysis. Life cycle inventory (LCI) results can allow to identify the environmental aspects and impacts of the manufacturing process, in the present case, the mechanical gearbox. These methodologies contribute to the continuous investment in innovation of the industrial sector as it aligns itself with environmental responsibilities (Oliveira; Matos; Pereira, 2017). The objective of this study was to carry out a Life cycle inventory (LCI) of the product system within the boundaries of the manufacturer, e.g., gate-to-gate. This was conducted with primary data collection and block diagram methodology.

2. METHODOLOGY

The simplified LCA used in this study was based on established methodologies and contained the 4 stages defined in standards NBR ISO 14040 (ABNT, 2014a) and 14044 (ABNT, 2014b). These were goal an-d scope definition, inventory analysis and interpretation of results as shown in Figure 01.

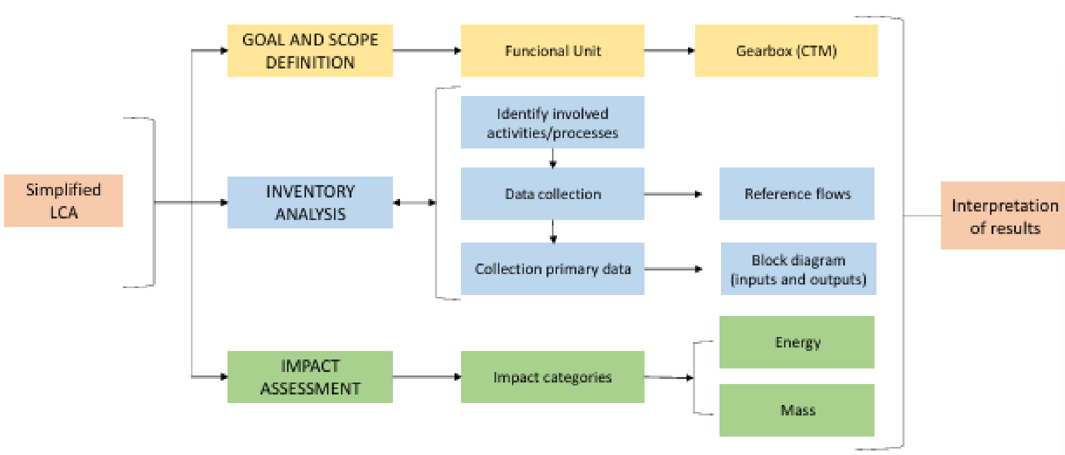

Figure 1: Methodology applied in the experimental program.
Source: The authors

2.1. Simplified LCA Stages

2.1.1. Goal and Scope Definition

The objective of this study was to conduct a simplified LCA of a mechanical gearbox used primarily in agricultural equipment. The manufacturer was a metal-mechanic business specialized in machinery and related equipment, henceforth referred to as Business A.

The functional unit (FU) of the study was a mechanical gearbox (MG) and the scope was its manufacturing process at Business A. The MG has commercial applications in farm equipment such as spreaders, distributors and seeders. It has a mass of approximately 6.5 kg and can be used either as a multiplier or redactor with an input rotation of 540 rpm or 1,000 rpm.

The system boundaries of this study were mechanical components manufactured in-house, gate-to-gate, by Business A for the mechanical gearbox. These were the housing, gears, axles and the assembly process of the gearbox.

2.1.2. Life Cycle Inventory analysis (LCI)

Data collection was conducted in loco within the boundaries of the system. Inflows considered were energy, raw materials and auxiliary items. Outflows were co-products and wastes. Water, oil, lubricants and hydraulic fluids used in the manufacture of an FU were also considered.

The methodology broke down the production system of an FU into separate processes. Each process was based on specific items manufactured in this process, which were: housing, crown gear, pinion gear, axle 1, axle 2 and assembly.

Based on data collected, reference flows were determined for the manufacturing process of a mechanical gearbox. These flows made use of symbols that allowed easy identification and understanding of the primary processes for all members of the study. Furthermore, they allowed block diagrams to be drawn up for the entire manufacturing process.

Flowcharts were produced for each process based on in loco knowledge shared through diagrams and manufacturing invoices (MFG) of each item. Due to non-disclosure agreements, these were not presented or referenced in this study.

The live cycle inventory (LCI) was determined from collected data and process flows. From it, block diagrams were created for the entire MG product system. Table 01 shows a sample block diagram based on Excel® spreadsheet software.

Product Sistem	Functional unit			Intermediate product	Functional unit part			
Inflow				Stage	Outflow			
Elementary inflow	Quantity	Units	Classification check	Elementary process	Elementary outflow	Quantity	Units	Classification check

Table 1: Sample table for compiling data into inventory block diagrams of process inflows and outflows.
Source: The authors.

Mass balances in the block diagrams were calculated for an FU from total monthly data collected from production management software used by Business A, namely, Codi® and Tecnicon®.

Elementary outflow of contaminated waste from the machining process was calculated in the LCI through the net flow of soluble oil and hydraulic oil. Solid metallic waste generation was calculated from the weight difference of the part before and after machining. Induction heating was used for forging and cooling made use of a closed-system cooling tower. This use of a natural, renewable resource promoted conservation and decreased environmental impact. Heat produced by the induction process was quantified from occupational hazard guidelines, which was part of Business A waste management program (WMP). Again, due to non-disclosure agreements, the WMP was not presented in this study. However, the environmental heat tolerance limit was listed in Regulation Standard 15 from Ministério do Trabalho (BRASIL, 2022b).

Elementary inflows included inserts, broaches and hobbing tools used in machining. Hobbing of the gear teeth made use of a Gleason Pentac gear cutting system. These tools were not included in elementary outflows of metallic waste since they were reused within the manufacturing process or returned to suppliers. For example, all edges of hard metal inserts containing tungsten carbide were used up to their useful lifespan limit and returned to the supplier, which in turn reincorporated them in their manufacturing process as a co-product. This procedure prevented the disposal of hard metals in industrial landfills. The hobbing Gleason Pentac system was sharpened in-house after each use as were the broaches until the end of their useful lifespan.

Energy balances in the block diagram were calculated from electrical consumption by applying Eq. (1) to all equipment used in the manufacturing process of an FU. Nominal power consumptions (Pe) were taken from technical specifications of each equipment and operational times (t) were measured in loco with Tecnicon® software.

$$EE = Pet \quad (1)$$

Validation of LCI data was necessary to ensure quality and identify faults. This was conducted by first confirming that all MG manufacturing data were included in the LCI by comparing it to written process descriptions and work instructions provided by Business A with ISO 9001:2015 certification.

Data trustworthiness was evaluated with the methodology of Kappler et al. (2018) at the inventory stage as seen in Figure 02. This methodology separated data sources individually and converted each into a mass fraction of an FU. Data for each material could be classified in up to 5 levels, which could be multiplied by their corresponding process to yield a final value between 1 and 25. Results are shown in Table 02 with lowest classification values indicating higher trustworthiness.

Classification	Description
1	Checked measured data
2	Unchecked measured data
3	Unchecked data partially taken from measureme
4	Qualified estimates
5	Unqualified estimates

Table 2: Data trustworthiness classification for LCI data
Source: Adapted from Kappler *et al.* (2018).

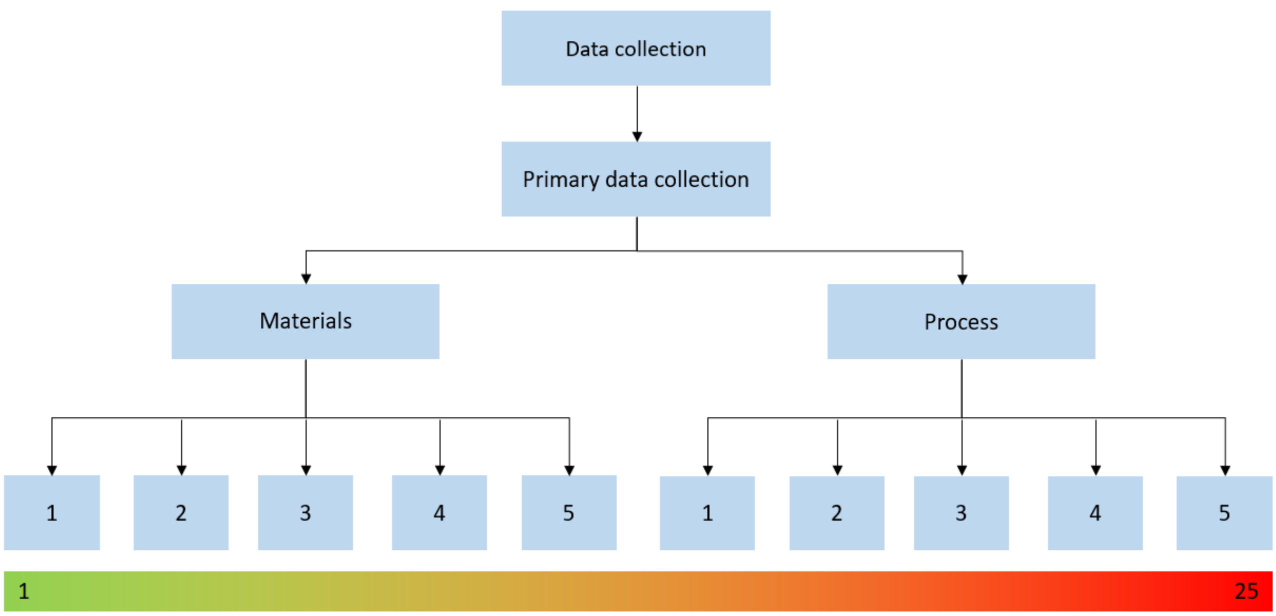

Figure 2: Evaluation flowchart for data trustworthiness of the LCI of this study.
Source: Adapted from Kappler *et al.* (2018).

2.2 Evaluation of the Environmental Aspects and Impacts

After the LCI accounted for all inflows and outflows of the manufacturing process of an FU, a environmental aspects and impacts could be conducted. To this end, the ReCiPe methodology was applied which made use of 18 midpoint indicators associated with 3 endpoint indicators:

a) Damage to human health (in DALY – disability-adjusted life year): this included climate change, ozone depletion, human toxicity, photo-chemical formation, particulate matter and ionizing radiation;

b) Damage to ecosystems (in species/year): this included ecosystem climate change, terrestrial acidification, fresh water eutrophication,

terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, land use transformation and agricultural and urban land occupation;
c) Damage to resource availability (in monetary $ units): this included mineral resources and fossil resources.

Several studies have applied the ReCiPe methodology. The LCA of Maheshwari et al. (2023) applied ReCiPe to compare 2 manufacturing processes of Inconel alloy 625. Kokare et al. (2023) applied all 18 midpoint indicators to two additive manufacturing processes of a marine propeller: wire arc additive manufacturing (WAAM) and selective laser melting (SLM) compared to conventional computer numerical control (CNC) hobbing. Lastly, Landi et al. (2022) also applied all 18 midpoints to compare the lifecycle of straight gears manufactured with additive laser manufacturing or conventional techniques.

It should be noted that, as an LCA progresses, it might be necessary to include/exclude categories based on environmental impacts identified upon completion of the LCI. In this study, the LCI was used to classify aspects and impacts of the manufacturing process of both intermediate products and the FU into relevant categories. However, no specific LCA software was used for the calculations.

3. RESULTS AND DISCUSSION

3.1. Functional Unit and System Boundaries

The functional unit (FU) of this study was a mechanical gearbox (MG) while system boundaries were items manufactured internally by Business A as seen in Figure 3, these were the housing, crown gear, pinion gear, axle 1 and axle 2.

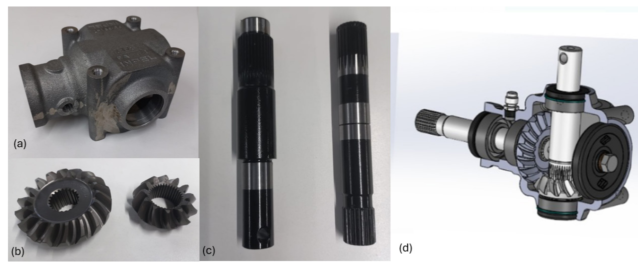

Figure 3: Items manufactured internally for the mechanical gearbox and FU: (a) housing; (b) crown gear and pinion gear; (c) axle 1 and axle 2 and (d) FU.
Source: The authors.

3.2. Reference Flow

Reference flows were determined from data collected in loco at Business A. For the assembly of the MG, other items that make up the FU were also manufactured in-house. The resulting manufacturing process flowcharts are shown in Figures 4 through Figure 7.

The manufacturing process for the housing started by separating smelted steel parts from raw material supplies. This material was sourced from outside system boundaries. The part was machined in a machining cell in 3 steps as shown in Figure 04. After washing, the part underwent quality control and sent to storage

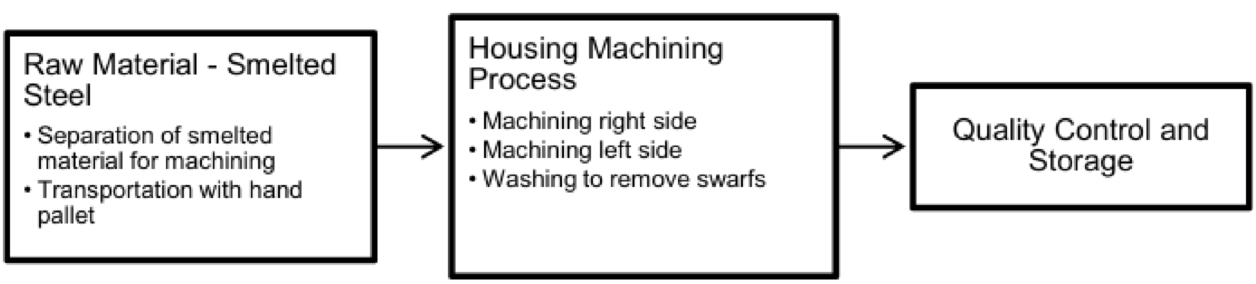

Figure 4: Manufacturing process flowchart of the housing used in the FU of this study.
Source: The authors.

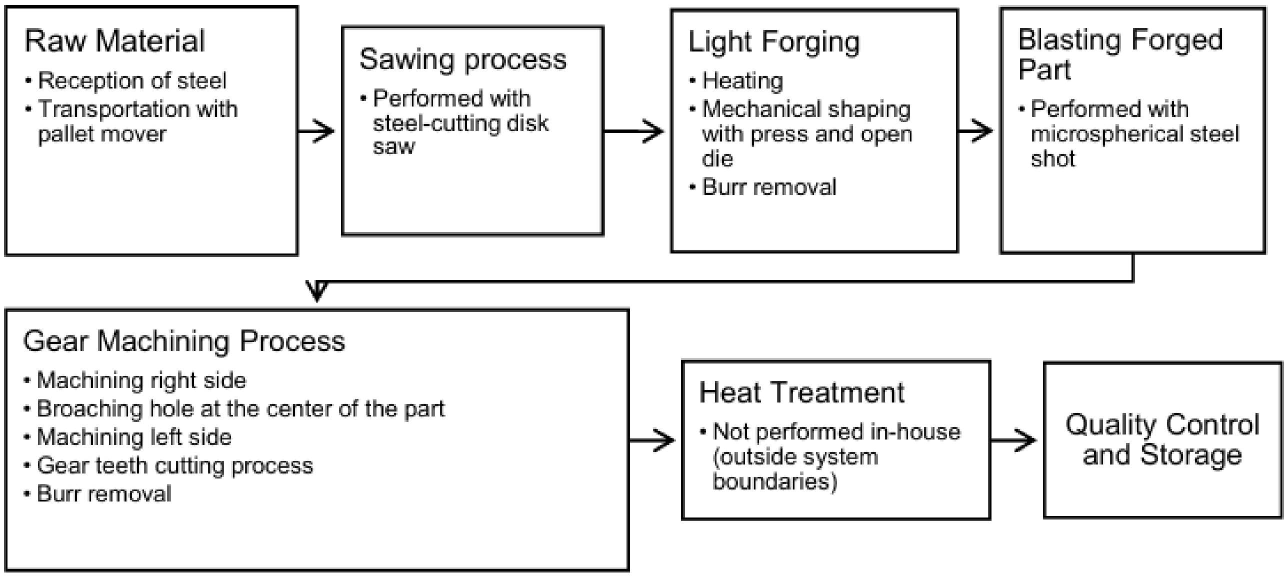

Figure 5: Manufacturing process flowchart of the crown gear or pinion gear used in the FU of this study

Source: The authors.

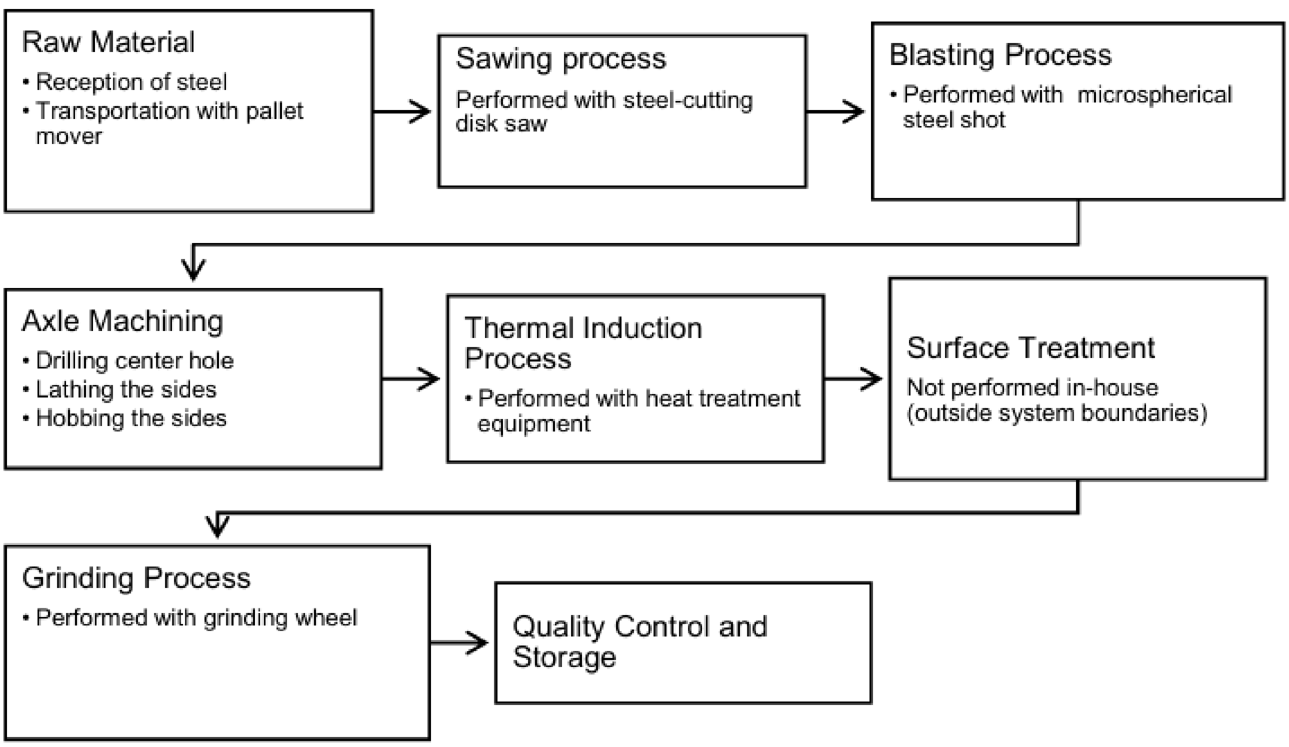

Figure 6: Manufacturing process flowchart of Axle 1 and Axle 2 used in the FU of this study.

Source: The authors.

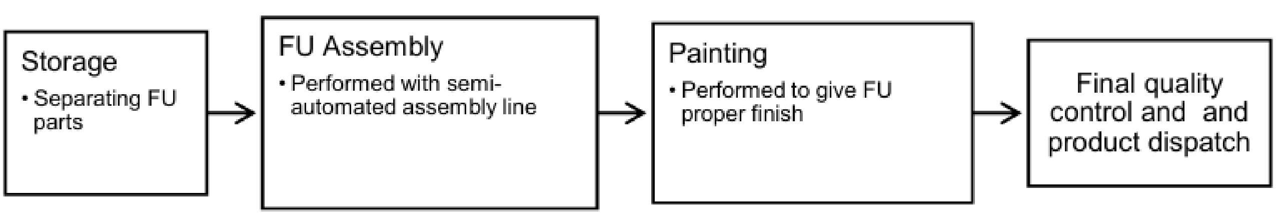

Figure 7: Manufacturing process flowchart of FU assembly for this study.

Source: The authors.

The manufacturing process of gears and axles started with a common first step of reception of steel bars. These materials were accompanied by a manufacturing invoice (MFG). Although not included in the references, this document contained specifications regarding the chemical composition of the steel, dimensions of the parts etc. The second common step in the manufacturing process was cutting with circular saws down to the dimensions required for each part.

Following cutting of the raw material, crown gears and pinion gears underwent a forging process consisting of heating under induction, shaping with an open die in an eccentric press and burr removal. After forging, blasting with micro-spherical steel shot was conducted to remove scales. Gears were machined in a gear machining cell in 5 steps as shown in Figure 05. The resulting conical helicoid gears were heat treated by a 3rd party contractor outside system boundaries. Upon return, the parts were checked for quality control and sent to storage.

Following cutting of the raw material, the manufacturing process of Axle 1 and Axle 2 consisted of blasting followed by machining. Machining was conducted in an axle machining cell in 3 steps as shown in Figure 06. The axles were tempered by induction heating followed by quenching to increase surface hardness. Surface treatment, which consisted of painting, was conducted outside system boundaries. Upon return, a grinding process was performed to adjust dimensions in accordance to design requirements. Finally, the axles were inspected for quality control and sent to storage.

The FU assembly process flowchart is shown in Figure 07. The process started with the separation of parts from storage. This step included items that were manufactured outside system boundaries. Parts were fed to an automated assembly line for assembly of the FU. The completed FU was sent to a painting line and finished its manufacturing process with quality control and delivery to dispatch.

3.3. Evaluation of the Environmental Aspects and Impacts

The Environmental Aspects and Impacts was conducted with data collected in loco and the manufacturing flowcharts presented in Section 3.2. The resulting block diagrams of the manufacturing process of the MG were developed on Excel® spreadsheet software and are presented in Annex 1.

Business A had a waste management program (WMP) in accordance to the national PNRS (BRASIL, 2010). The PNRS listed types and amounts of solid wastes and their corresponding proper environmental separation, collection, storage, transport, recycling, destination and final disposal.

In accordance to environmental license regulations, effluents from the elementary outflow of machining processes were sent for external treatment at another business located in the state of Rio Grande do Sul. Treatment consisted of separation of oil and water through a physical process of evaporation under controlled temperature. Metallic waste destination started with in loco collection on a conveyor belt to a waste trolley. The collected waste was stored in a designated solid waste storage area (SWSA) where separation occurred in accordance to the WMP of Business A. Separated waste was then sold to licensed recycling businesses. The LCA conducted by Garbin et al. (2023) obtained environmental gains from recycling metallic waste associated with global warming (GWP 100a), acidity, human toxicity (air, water and soil) and ozone layer destruction. However, recycling associated with other categories had a negative gains due to high energy consumption requirements. Swarf from machining contained a degree of waste oil contamination. Business A separated the oil prior to swarf recycling by placing the waste on a perforated screen over a collection basin. Accumulated oil over 2 days was drained from the bottom of the basin, filtered and fed back to the machining cell equipment. Simon et al. (2017) evaluated this procedure as highly eco-efficient.

Class I solid waste generated were abrasive particles from blasting, scales from grinding and paint-contaminated waste from painting. These were sent to a specialized business licensed to handle Class I and II waste. Waste with significant energy content was converted into fuel while non-energetic wastes were forwarded for thermal disposal or used as replacement material in the production of cement. Araujo (2020) noted that the co-processing of waste in the cement industry was a suitable option for sustainability since it encompassed social, economic and environmental aspects. However, the LCA of Garbin et al. (2023) pointed out potentially negative environmental impacts in the incineration of dangerous wastes which were generated in all impact categories of this study.

3.3.1. Mass Balance

Table 04 presents the resulting inflow and outflow mass balances of intermediate products used in the FU. The mass balance identified that the larger proportion of solid metallic waste were generated from the manufacture of crown gear (35 %) and pinion gear (59 %) intermediate products.

Intermediate product	Raw material (kg)	Solid metallic waste (kg)	%
Housing	3.9090	0.4560	12%
Pinion gear	0.4830	0.2870	**59%**
Crown gear	0.816	0.2896	**35%**
Axle 1	1.130	0.2800	25%
Axle 2	0.800	0.17	21%

Table 4: Mass balance of intermediate products of the FU.
Source: The authors.

The detailed individual mass balance of the pinion gear presented in Table 05 breaks down the elementary processes that make up the 59 % metallic solid waste generated from the machining process. Table 05 shows that 23 % of the waste originated from machining the right side, which involved drilling through the center of the gear. Table 05 also shows that the crown gear generated less waste when compared to the pinion gear even though both parts had the same elementary processes. This was due to the crown gear geometry having final dimensions close to the location where gear teeth were hobbed. Consequently, gear hobbing accounted for 16% of waste for the crown gear but 26% for the pinion gear.

As shown in Table 05, the open die forging technique currently used generated 25% and 8% of solid waste for the crown and pinion gears, respectively. As noted by Flausino (2010), shaping provided by a close die offered improved control over the inflow of raw materials and reduced or eliminated swarf. Consequently, replacing the open die with a closed one with a shape in accordance with the final part would directly decrease the consumption of raw materials and waste generation.

Elementary Process	Raw Material (kg)	Solid metallic Residue (kg)	%
Crown Gear			
Steel cutting process	0.8161	0.0001	0%
Mechanical shaping with press and open die	0.8160	0.0000	0%
Light forging and swarf removal	0.8160	0.0723	25%
Right side machining	0.7437	0.0973	34%
Broaching center hole	0.6464	0.0085	3%
Left side machining	0.6379	0.0663	23%
Gear hobbing process	0.5716	0.0451	16%
Pinion Gear			
Steel cutting process	0.4831	0.0001	0%
Mechanical shaping with press and open die	0.4830	0.0000	0%
Light forging and swarf removal	0.4830	0.0392	8%
Right side machining	0.4438	0.1034	23%
Broaching center hole	0.3404	0.0107	3%
Left side machining	0.3297	0.0646	20%
Gear hobbing process	0.2652	0.0691	26%

Table 5: Break down of crown gear and pinion gear mass balance.
Source: The authors.

3.3.2. Energy Balance

Table 06 presents inflow and outflow energy balances of the manufacturing processes of the intermediate products used in the FU of this study. As shown in Table 06, the manufacture of a single FU of this study consumed 59.967 kWh of electricity. The energy balance of intermediate products identified that gear manufacture consumed the most energy due to the nominal power of the equipment. In comparison, axle manufacturing, while operating over the same length of time, consumed less energy.

Business A sought to decrease the environmental impact of energy consumption by acquiring its monthly electricity demand of 0.4 MW, which accounted for all manufacturing processes, from the free energy market since 2018. This switch to the free market model could favor renewable energy sources since suppliers were free to acquire energy from federal auctions and provide service to their customers at variable rates (CEEE, 2022).

The industrial sector in Brazil accounted for 34.1 % of total consumption in 2021 as noted by the Atlas da Eficiência Energética (BRASIL, 2022b). The main energy sources for the industrial sector in 2020 were reported as sugarcane bagasse (22 %), electricity (21 %) and coal and derivatives (14 %) (BRASIL, 2021). In the case of Business A, its energy consumption and characteristic floor area suggested a possible change in energy matrix from a traditional model to photovoltaic, pending a detailed economic and environmental investment evaluation.

Intermediate Product	Nominal Power (kW)	Operating Time/FU (h)	Energy Consumption / FU (kWh)
Housing	42.240	0.1000	4.224
Pinion gear	431.748	0.0333	14.392
Crown gear	431.748	0.0333	14.392
Axle 1	290.208	0.0333	9.674
Axle 2	290.208	0.0333	9.674
Assembly	59.300	0.0778	4.612
Total energy consumed / FU (kWh)			**56.967**

Table 6: Energy balance of intermediate products for the FU of this study.
Source: The authors.

3.4. Evaluation of the Environmental Aspects and Impacts

Table 07 presents the aspects and impacts of the manufacturing process of the FU based on the inventory analysis of inflows and outflows. Business A belonged to the metal-mechanical sector and its manufacturing processes mostly consisted of machining. Consequently, as shown in Table 07, aspects and impacts were repeated in all processes. Impact categories for LCIA were related to Damages to Resource Availability in the ReCiPe methodology, although no specialized software was used in the analysis.

Regarding the use of steel and its contribution to the decrease in natural resources, it was concluded that the small quantities used in the production of the FU posed no probability of resource depletion. The steel used as raw material for gears and axles were imported from overseas suppliers due to economic reasons and laid outside system boundaries. Thus the only possible opportunities for reducing environmental impact were the ones presented in Sec. 3.3.1.

Electricity consumption also presented an impact of decrease in natural resources. This was directly related to the Brazilian energy generation matrix, which was 72 % hydroelectric, 12. 9% wind power and 9.9 % thermoelectric (ONS, 2023). Business A currently acquired electricity from free market suppliers and the LCIA recommended investing in photovoltaic power generation if further studies confirmed its viability.

Process	Aspect	Impact	LCIA	
			Impact Category	Indicator
Housing, pinion gear, crown gear, Axle 1 and Axle 2	Materials consumed in small quantities ando no probability of natural resource depletion. Raw material: steel	Decrease in Natural Resources	Resource Consumption	kg per FU
	Materials consumed in small wantities with probability of natural resource depletion. Used in inserts: rare metals	Decrease in Natural Resources	Resource Consumption	kg per FU
	Use of natural resource: water	Decrease in Natural Resources	Resource Consumption	L per FU
	Electricity consumption	Decrease in Natural Resources	Resource Consumption	kWh per FU
	Noise emissions	Sound Pollution	-	-
	Atmospheric emissions	Changes in air quality	-	-
	Solid waste generation	Changes in soil and water quality	Resource Consumption	kg per FU
	Contaminated effluent emissions	Changes in soil and water quality	Resource Consumption	L per FU
Assembly	Chemical productis consumed in small quantities: non-halogenated solvents and paints	Decrease in Natural Resources	Resource Consumption	L per FU
	Noise emissions	Sound Pollution	-	-
	Electricity consumption	Decrease in Natural Resources	Resource Consumption	kWh per FU
	Solid waste generation	Changes in soil and water quality	Resource Consumption	kg per FU

Table 7: Processes Aspects and Impacts on FU production.
Source: The authors.

Changes in soil and water quality were impacts related to Class I solid waste generation from the manufacturing process and contaminated effluents from machinery cleaning processes. Steps taken by Business A to mitigate environmental impacts and use of industrial landfills were to send Class I waste for co-processing and effluents for treatment at outside businesses, as required by environmental legislation. Thus, no direct environmental onus was laid at Business A.

Regarding noise emissions from operating machinery, impacts and mitigating steps were evaluated in accordance with directives from regulating agencies and reported as required for environmental operating licenses. Atmospheric emissions from oil and paint spray associated with changes in air quality were mitigated by monitoring and replacing exhaust filters as recommended by suppliers.

Overall, the identified environmental impacts associated with the production of the FU and current adopted mitigating steps demonstrated that Business A was concerned with environmental issues and compliant with environmental legislation.

4. CONCLUSIONS

Currently, while the industrial sector continuously invests in improvements to manufacturing processes, customers also demand attention from businesses and products to environmental concerns. An LCA methodology can attend to both issues since it can identify opportunities in manufacturing processes that improve environmental performance of a product along its life cycle. The resulting efforts could be further used in the production of public relation materials with positive marketing potential.

This study applied a simplified LCA to the manufacturing process of a mechanical gearbox through mass and energy balances and block diagram methodology. System boundaries were defined as items manufactured in-house. The goal and scope were the life cycle of a single mechanical gearbox FU through manufacturing process flows. Primary data collected in loco were used as base to construct inventory inflow and outflow through block diagrams.

The inventory inflow and outflow allowed the calculation of mass balances of metallic solid waste in the manufacturing process of an FU both globally as well as for individual intermediate products. For example, the pinion gear intermediate product accounted for 59 % solid waste generation. A breakdown of the elementary processes of the pinion gear identified that machining the right side and gear hobbing accounted for 23 % and 26 % of solid waste generated, respectively.

The evaluation of the environmental aspects and impacts of the mechanical gearbox FU manufacturing process identified the decrease of natural resources as the major impact affecting all processes, followed by changes to soil and water quality. Data collected in 2021 demonstrated that Business A already engaged in environmentally conscious practices. It was concluded that the use of a simplified LCA as an environmental management tool could aid in directing future initiatives to further mitigate environmental impacts.

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ANNEX 1

Product System	Mechanical Gearbox (MG)			Intermediate Product	Housing			
Inflow				Stage	Outflow			
Elementary inflow	Quantity	Units	Classification	Elementary process	Elementary outflow	Quantity	Units	Classification
Smelted steel	3.9090	kg	1	Transport on hand pallet	Smelted steel	3.9090	kg	1
LPG (gas)	0.0001	m^3	4		Atmospheric emissions	Undetermined		
Hydraulic oil	3rd party service				Hydraulic oil (used)	3rd party service		
Smelted steel	3.9090	kg	1	Right side machining	Housing machining – right side	3.7700	kg	1
Inserts	0.0046	un	1		Solid waste (metal)	0.1390	kg	1
Electricity	1.6	kWh	4		Inserts (used)	0.0046	un	1
Soluble oil	0.0042	L	4		Contaminated effluent	0.0050	L	4
Hydraulic oil	0.0008	L	4		Atmospheric emissions	Undetermined		
Housing machining – right side	3.77	kg	1	Left side machining	Housing	3.4530	kg	1
Inserts	0.0066	un	1		Solid waste (metal)	0.3170	kg	1
Electricity	1.5	kWh	4		Inserts (used)	0.0066	un	1
Soluble oil	0.0042	L	4		Contaminated effluent	0.0050	L	4
Hydraulic oil	0.0008	L	4		Atmospheric emissions	Undetermined		
Housing	3.453	kg	1	Washer	Housing	3.4530	kg	1
Water	0.0083	L	5		Contaminated effluent	0.0249	L	5
Electricity	1.1	kWh	4		Atmospheric emissions	Undetermined		
Hydraulic oil	0.0166	L	1					
Housing	3.4530	kg	1	Transport on pallet carrier	Housing	3.4530	kg	1
Electricity	0.0240	kWh	4					

Table 3: Inventory inflows and outflows for the manufacture of the housing used in the FU of this study.
Source: The authors.

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Product System	Mechanical Gearbox (MG)			**Intermediate Product**	Pinion gear			
Inflow				**Stage**	**Outflow**			
Elementary inflow	Quantity	Units	Classification	Elementary process	Elementary outflow	Quantity	Units	Classification
Steel bar	26.947	kg	1	Transport by hoist	Steel bar	26.947	kg	1
Electricity	0.0111	kWh	4					
Steel bar	26.947	kg	1	Steel cutting with disk saw	Saw 1	0.483	kg	1
Disk saw	0.0005	un	1		Solid waste (metal)	0.0001	kg	1
Electricity	0.1042	kWh	4		Disk saw waste	0.0005	un	1
Cutting oil	0.0013	L	1		Contaminated effluent	0.0025	L	1
Hydraulic oil	0.0012	L	1		Atmospheric emissions	Undetermined		
Saw 1	0.4830	kg	1	Part heating	Heated saw 1	0.4830	kg	1
Electricity	1.6667	kWh	4		Heat	26.8	°C	1
Cooling system (water)	200.00	L	4		Cooling system (water)	200.00	L	4
Heated saw 1	0.4830	kg	1	Shaping with press and open die	Forged part 1	0.4830	kg	1
Electricity	0.6214	kWh	4		Contaminated effluent	0.0057	L	1
Demolder	0.0057	L	1					
Forged part 1	0.4830	kg	1	Scale removal	Forged part 1	0.4438	kg	1
Electricity	0.1022	kWh	4		Solid waste (metal)	0.0392	kg	1
Forged part 1	0.4438	kg	1	Transport by pallet carrier	Forged part 1	0.4438	kg	1
LPG (gas)	0.0001	m^3	4		Atmospheric emissions	Undetermined		
Hydraulic oil	3rd party service							
Forged part	0.4438	kg	1	Blasting	Pinion gear	0.4438	kg	1
Blasting steel material	0.0053	kg	1		Solid waste (Class I)	0.0053	kg	1
Electricity	0.1144	kWh	4		Atmospheric emissions	Undetermined		
Air filter	0.0003	un	1		Solid waste (Class I)	0.0003	un	1

Pinion gear	0.4438	kg	1	Righs side machining	Pinion gear	0.3404	kg	1
Inserts	0.0048	un	1		Solid waste (metal)	0.1034	kg	1
Electricity	1.2667	kWh	4		Contaminated effluent	0.0031	L	1
Soluble oil	0.0012	L	1		Inserts (used)	0.0048		1
Hydraulic oil	0.0019	L	1		Atmospheric emissions	Undetermined		
Pinion gear	0.3404	kg	1	Broaching center of the part	Pinion gear	0.3297	kg	1
Broach	0.0004	un	1		Solid waste (metal)	0.0107	kg	1
Electricity	0.7333	kWh	4		Contaminated effluent	0.0023	L	1
Soluble oil	0.0012	L	1		Broach (used)	0.0004	un	1
Hydraulic oil	0.0010	L	1		Atmospheric emissions	Undetermined		
Pinion gear	0.3297	kg	1	Machining	Pinion gear	0.2652	kg	1
Inserts	0.0031	un	1		Solid waste (metal)	0.0646	kg	1
Electricity	1.2667	kWh	4		Contaminated effluent	0.0021	L	1
Soluble oil	0.0012	L	1		Inserts (used)	0.0031	un	1
Hydraulic oil	0.0008	L	1		Atmospheric emissions	Undetermined		
Pinion gear	0.2652	kg	1	Gear teeth cutting	Pinion gear	0.1961	kg	1
Pentac cutter	1.0000	un	1		Solid waste (metal)	0.0691	kg	1
Electricity	2.7667	kWh	4		Pentac cutter (used)	1.0000	un	1
Soluble oil	0.00176	L	1		Contaminated effluent	0.0176	L	1
Water	0.0158	L	1		Atmospheric emissions	Undetermined		
Pinion gear	0.1961	kg	1	Swarf removal	Pinion gear	0.1961	kg	1
Disk saw	0.0010	un	1		Solid waste (metal)	0.0000	kg	1
					Disk saw (used)	0.0010	un	1
Electricity	0.0667	kWh	4		Atmospheric emissions	Undetermined		
Lubricant oil	0.0007	L	1		Contaminated effluent	0.0007	L	1
Pinion gear	0.1961	kg	1	Transport by pallet carrier to storage	Pinion gear	0.1961	kg	1
Electricity	0.0240	kWh	4					

Table 4: Inventory inflows and outflows for the manufacture of the pinion gear used in the FU of this study.

Source: The authors.

Product System	Mechanical Gearbox (MG)			**Intermediate Product**	Crown gear			
Inflow				**Stage**	**Outflow**			
Elementary inflow	Quantity	Units	Classification	Elementary process	Elementary outflow	Quantity	Units	Classification
Steel bar	26.947	kg	1	Transport by hoist	Steel bar	26.947	kg	1
Electricity	0.0111	kWh	4					
Steel bar	26.947	kg	1	Steel cutting with saw disk	Saw 2	0.8160	kg	1
Saw disk	0.0005	un	1		Solid waste (metal)	0.0001	kg	1
Electricity	0.1042	kWh	4		Contaminated effluent	0.0025	L	1
Cutting oil	0.0013	L	1		Saw disk (used)	0.0005	un	1
Hydraulic oil	0.0012	L	1		Atmospheric emissions	Undetermined		
Saw 2	0.8160	kg	1	Part heating	Heated saw 2	0.8160	kg	1
Electricity	1.6667	kWh	4		Heat	26.8	°C	1
Cooling system (water)	200.00	L	4		Cooling system (water)	200.00	L	4
Heated saw 2	0.8160	kg	1	Shaping with press and open die	Forged part 2	0.8160	kg	1
Electricity	0.6214	kWh	4		Contaminated effluent	0.0057	L	1
Demolder	0.0057	L	1					
Forged part 2	0.8160	kg	1	Scale removal	Forged part 2	0.7437	kg	1
Electricity	0.1022	kWh	4		Solid waste (metal)	0.0723	kg	1
Forged part 2	0.7437	kg	1	Transport by pallet carrier	Forged part 2	0.7437	kg	1
LPG (gas)	0.0001	m^3	4		Atmospheric emissions	Undetermined		
Hydraulic oil	3rd party maintenance							
Forged part 2	0.7437	kg	1	Blasting	Crown gear	0.7437	kg	1
Blasting material	0.0057	kg	1		Solid waste (Class I)	0.0057	kg	1
Electricity	0.1144	kWh	4		Atmospheric emissions	Undetermined		

Table 5: Inventory inflows and outflows for the manufacture of the crown gear used in the FU of this study.

Source: The authors.

Crown gear	0.7437	kg	1	Matchining right side	Crown gear - right side	0.6464	kg	1
Inserts	0.0048	un	1		Solid waste (metal)	0.0973	kg	1
Electricity	1.2667	kWh	4		Contaminated effluent	0.0031	L	1
Soluble oil	0.0012	L	1		Inserts (used)	0.0048	un	1
Hydraulic oil	0.0019	L	1		Atmospheric emissions	Undetermined		
Crown gear - right side	0.6464	kg	1	Broaching center of the part	Crown gear right side broach	0.6379	kg	1
Broach	0.0004	un	1		Solid waste (metal)	0.0085	kg	1
Electricity	0.7333	kWh	4		Contaminated effluent	0.0023	L	1
Soluble oil	0.0012	L	1		Broach (used)	0.0004	un	1
Hydraulic oil	0.0010	L	1		Atmospheric emissions	Undetermined		
Crown gear - right side broach	0.6379	kg	1	Machining	Crown gear	0.5716	kg	1
Inserts	0.0031	un	1		Solid waste (metal)	0.0663	kg	1
Electricity	1.2667	kWh	4		Contaminated effluent	0.0021	L	1
Soluble oil	0.0012	L	1		Inserts (used)	0.0031	un	1
Hydraulic oil	0.0008	L	1		Atmospheric emissions	Undetermined		
Crown gear	0.5716	kg	1	Gear teeth cutting	Crown gear	0.5265	kg	1
Pentac cutter	1.0000	un	1		Solid waste (metal)	0.0451	kg	1
Electricity	2.7667	kWh	4		Atmospheric emissions	Undetermined		
Soluble oil	0.0018	L	1		Contaminated effluent	0.0176	L	1
Water	0.0158	L	1		Pentac cutter (used)	1.0000	un	1
Crown gear	0.5265	kg	1	Swarf removal	Crown gear	0.5265	kg	1
Saw disk	0.0010	un	1		Saw disk (used)	0.0010	un	1
					Solid waste (metal)	0.0000	kg	1
Eletricity	0.0667	kWh	4		Atmospheric emissions	Undetermined		
Lubricating oil	0.0007	L	1		Contaminated effluent	0.0007	L	1
Crown gear	0.5265	kg	1	Transport by pallet carrier to storage	Crown gear	0.5265	kg	1
Electricity	0.0240	kWh	4					

Table 5: Inventory inflows and outflows for the manufacture of the crown gear used in the FU of this study (cont.)

Source: The authors.

Product System	Mechanical Gearbox (MG)			Intermediate Product	Axle 1			
Inflow				Stage	Outflow			
Elementary inflow	Quantity	Units	Classification	Elementary process	Elementary outflow	Quantity	Units	Classification
Steel bar	37.2910	kg	1	Transport by hoist	Steel bar	37.2910	kg	1
Electricity	0.0111	kWh	4					
Steel bar	37.2910	kg	1	Steel cutting with disk saw	Saw 3	1.1300	kg	1
Saw disk	0.0005	un	1		Solid waste (metal)	0.0100	kg	1
Electricity	0.0613	kWh	4		Contaminated effluent	0.0626	L	1
Cutting oil	0.0013	L	1		Atmospheric emissions	Undetermined		
Hydraulic oil	0.0012	L	1		Saw disk (used)	0.0005	un	1
Saw 3	1.1300	kg	1	Transport by pallet carrier	Saw 3	1.1300	kg	1
LPG (gas)	0.0001	m^3	4		Atmospheric emissions	Undetermined		
Hydraulic oil	3rd party maintenance				Hydraulic oil	3rd party maintenance		
Saw 3	1.1300	kg	1	Blasting	Axle 1	1.1300	kg	1
Blasting steel material	0.0057	kg	1		Solid waste (Class I)	0.0057	kg	1
Electricity	0.1144	kWh	4		Atmospheric emissions	Undetermined		
Air filter	0.0003	un	1					
Axle 1	1.1300	kg	1	Drilling center of part	Axle 1 - center drilling	1.1000	kg	1
Inserts	0.0012	un	1		Solid waste (metal)	0.0300	kg	1
Electricity	0.5000	kWh	4		Contaminated effluent	0.0028	L	1
Soluble oil	0.0020	L	1		Inserts (used)	0.0012	un	1
Hydraulic oil	0.0008	L	1		Atmospheric emissions	Undetermined		
Axle 1 - center drilling	1.1000	kg	1	Lathing	Axle 1	0.8900	kg	1
Inserts	0.0078	un	1		Solid waste (metal)	0.2100	kg	1
Electricity	0.9194	kWh	4		Contaminated effluent	0.0028	L	1
Soluble oil	0.0020	L	1		Inserts (used)	0.0078	un	1
Hydraulic oil	0.0008	L	1		Atmospheric emissions	Undetermined		

Table 6: Inventory inflows and for the manufacture of the Axle 1 used in the FU of this study.

Source: The authors.

Axle 1	0.8900	kg	1	Hobbing the sides	Axle 1	0.8700	kg	1
Inserts	0.0003	un	1		Solid waste (metal)	0.0200	kg	1
Electricity	1.2667	kWh	4		Contaminated effluent	0.0030	L	1
Soluble oil	0.0004	L	1		Inserts (used)	0.0003	un	1
Hydraulic oil	0.0028	L	1		Atmospheric emissions	Undetermined		
Axle 1	0.8700	kg	1	Thermal induction treatment	Axle 1	0.8700	kg	1
Soluble oil	0.0020	L	1		Contaminated effluent	0.0031	L	1
Electricity	5.0000	kWh	4		Atmospheric emissions	Undetermined		
Lubricating oil	0.0009	L	1					
Soluble oil	0.0001	L	1					
Axle 1	0.8700	kg	1	Grinding	Axle 1	0.8600	kg	1
Grinder	0.0001	un	1		Solid waste (metal)	0.0100	kg	1
Electricity	0.8667	kWh	4		Contaminated effluent	0.0015	L	1
Lubricating oil	0.0002	L	1		Atmospheric emissions	Undetermined		
Hydraulic oil	0.0012	L	1		Solid waste (Class I)	0.0001	un	1
Axle 1	0.8600	kg	1	Transport by pallet carrier to storage	Axle 1	0.8600	kg	1
Electricity	0.0240	m^3	4					

Table 6: Inventory inflows and for the manufacture of the Axle 1 used in the FU of this study (cont.)

Source: The authors.

Product System	Mechanical Gearbox (MG)			**Intermediate Product**	Axle 1			
Inflow				**Stage**	**Outflow**			
Elementary inflow	Quantity	Units	Classification	Elementary process	Elementary outflow	Quantity	Units	Classification
Steel bar	26.9470	kg	1	Transport by hoist	Steel bar	26.9470	kg	1
Electricity	0.0111	kWh	4					
Steel bar	26.9470	kg	1	Steel cutting with disk saw	Saw 4	0.8000	kg	1
Saw disk	0.0005	un	1		Solid waste (metal)	0.0100	kg	1
Electricity	0.0613	kWh	4		Contaminated effluent	0.0626	L	1
Cutting oil	0.0013	L	1		Saw disk (used)	0.0005	un	1
Hydraulic oil	0.0012	L	1		Atmospheric emissions	Undetermined		

Table 7: Inventory inflows and outflows for the manufacture of the Axle 2 used in the FU of this study.

Source: The authors.

Saw 4	0.8000	kg		Transport by pallet carrier	Saw 4	0.8000	kg	
LPG (gas)	0.0001	m^3			Atmospheric emissions	Undetermined		
Hydraulic oil	3rd party maintenance				Hydraulic oil	3rd party maintenance		
Saw 4	0.8000	kg	1	Blasting	Axle 2	0.8000	kg	1
Blasting steel material	0.0057	kg	1		Solid waste (Class I)	0.0057	kg	1
Electricity	0.1144	kWh	4		Atmospheric emissions	Undetermined		
Air filter	0.0003	un	1					
Axle 2	0.8000	kg	1	Center hole drilling	Axle 2 - center drilling	0.7900	kg	1
Inserts	0.0012	un	1		Solid waste (metal)	0.0100	kg	1
Electricity	0.5000	kWh	4		Contaminated effluent	0.0028	L	1
Soluble oil	0.0020	L	1		Inserts (used)	0.0012	un	1
Hydraulic oil	0.0008	L	1		Atmospheric emissions	Undetermined		
Axle 2 - center hole	0.7900	kg	1	Lathing	Axle 2	0.6700	kg	1
Inserts	0.0078	un	1		Solid waste (metal)	0.1200	kg	1
Electricity	0.9194	kWh	4		Contaminated effluent	0.0028	L	1
Soluble oil	0.0020	L	1		Inserts (used)	0.0078	un	1
Hydraulic oil	0.0008	L	1		Atmospheric emissions	Undetermined		
Axle 2	0.6700	kg	1	Hobbing	Axle 2	0.6500	kg	1
Inserts	0.0003	un	1		Solid waste (metal)	0.0200	kg	1
Electricity	1.2667	kWh	4		Contaminated effluent	0.0030	L	1
Soluble oil	0.0004	L	1		Inserts (used)	0.0003	un	1
Hydraulic oil	0.0028	L	1		Atmospheric emissions	Undetermined		
Axle 2	0.6500	kg	1	Induction heat treatment	Axle 2	0.6500	kg	1
Soluble oil	0.0020	L	1		Contaminated effluent	0.0031	L	1
Electricity	5.0000	kWh	4		Atmospheric emissions	Undetermined		
Lubricating oil	0.0009	L	1					
Soluble oil	0.0001	L	1					

Table 7: Inventory inflows and outflows for the manufacture of the Axle 2 used in the FU of this study (cont.)

Source: The authors.

Axle 2	0.6500	kg	1	Grinding	Axle 2	0.6400	kg	1
Grindstone	0.0001	un	1		Solid waste (metal)	0.0100	kg	1
Electricity	0.8667	kWh	4		Contaminated effluent	0.0015	L	1
Lubricating oil	0.0002	L	1		Atmospheric emissions	Undetermined		
Hydraulic oil	0.0012	L	1		Solid waste (Class I)	0.0001	un	1
Axle 2	0.6400	kg	1	Transport by pallet carrier to storage	Axle 2	0.6400	kg	1
Electricity	0.0240	m^3	4					

Table 7: Inventory inflows and outflows for the manufacture of the Axle 2 used in the FU of this study (cont.)

Source: The authors.

Product System	Mechanical Gearbox (MG)			Intermediate Product	Assembly			
Inflow				**Stage**	**Outflow**			
Elementary inflow	Quantity	Units	Classification	Elementary process	Elementary outflow	Quantity	Units	Classification
Housing	3.4530	kg	1	Semi-automated FU assembly	MG	6.3500	kg	1
Pinion gear	0.1961	kg	1					
Crown gear	0.5264	kg	1					
Axle 1	0.8600	kg	1					
Axle 2	0.6400	kg	1					
Oil	0.2500	L	1					
Miscelaneous parts	0.6744	kg	1					
Electricity	0.2567	kWh	4					
MG	6.3500	kg	1	Painting and Finishing	MG	6.3500	kg	1
Paint	0.007	L	1		Non-halogenated solvent effluent	0.003	L	1
Electricity	4.556	kWh	4		Solid waste (Class I)	0.002	un	1
Air filter	0.002	un	1		Atmospheric emissions	Undeterminated		
Solvent	0.003	L	1					

Table 7: Inventory inflows and outflows for the assembly of the FU of this study.

Source: The authors.