

FLASH

Flexible Laser-Based Manufacturing

D4.4 – Inventory of LCA data

HORIZON-CL4-2023-TWIN-TRANSITION-01-02.



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Flexible Laser-Based Manufacturing

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ABBREVIATIONS

AM	Additive manufacturing
CBN	Cubic boron nitride
CCB	Cross car beam
GW	Grinding wheel
GWP	Global Warming Potential
LCA	Life cycle assessment
LCI	Life cycle inventory
MRS	Mineral resource scarcity
PCD	Polycrystalline diamond
WC	Tungsten carbide

General Information

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Author	
Authoring partner	3drivers – Engenharia, Inovação e Ambiente, lda
Contact person	João Duarte
Email Phone	jduarte@3drivers.pt +351 912005304

Executive Summary

This final technical report presents the results obtained with the conclusion of the task T4.4- Life cycle inventory for use cases, i.e. the complete inventory of environmental relevant data sets for all life cycle stages of the current and the proposed laser technologies (water jet guided laser, surfacing, laser cutting). The task T4.4 is part of the work package WP4- Process development, modelling and metrology.

It was developed, based on the five use cases in the scope of FLASH, the life cycle inventory (LCI) and the LCA (Life Cycle Assessment) results, with environmental impact assessment for the several impact categories included in SimaPro (the software used for LCA modelling). Different scenarios were modelled, that compared a conventional scenario of producing a certain product (e.g. galvanic electroplating of the grinding wheel) with the same product produced with laser processes.

The results showed that the laser processes could have reductions in the global warming potential (GWP) from 3% (acetabular cup use case) to 85% (microdrills use case).

The inventories and the LCA information will then be used to integrate the cloud data management system.

1. INTRODUCTION

The manufacturing industry encompasses a broad and diverse range of businesses (automotive, biomedical, aeronautics and others). Direct carbon emissions from the manufacturing sector, which include process emissions but exclude indirect emissions from electricity use, contribute to 25% of global emissions in 2022, totaling approximately 9 gigatons of CO₂ (IEA, 2023). Therefore, it is essential to assess the environmental impact of key manufacturing processes and thus determine potential areas for improvement (Thirupathi *et al.*, 2018). In conventional manufacturing processes (CNC machining), material is either removed via machining, drilling, grinding or welding (Pereira *et al.*, 2019). Besides the mechanical conventional processes, that are also methods that adopt hazardous chemicals (Takuma *et al.*, 2017). Galvanic electroplating, or electrodeposition, relies on electrolysis to apply a thin metal layer onto a conductive surface, forming either a protective or decorative coating (Giurlani *et al.*, 2018). With the goal of reducing operation time, energy consumption and waste generation, different laser-based techniques have been implemented in the last decades (fiber, CO₂ and diode lasers) (Kellens, Rodrigues, *et al.*, 2014).

The FLASH project seeks to innovate laser processing by developing a multi-process laser system that enables flexible, customizable production while reducing energy consumption and material waste. By replacing conventional resource- and energy-intensive manufacturing steps with optimized laser-based processes, the project aims to demonstrate the potential of this technology across multiple industrial applications.

To systematically assess the environmental benefits of the FLASH system, Life Cycle Assessment (LCA) is applied to quantify key impact categories, such as global warming potential (GWP), resource depletion, and toxicity. The role of 3drivers in this task is to assess the environmental performance of FLASH laser processes (fiber and water jet guided laser) in comparison to existing manufacturing technologies across five industrial use cases: (i) manufacturing of acetabular cups for orthopedic hip implants, (ii) production of polycrystalline diamond micro drills, (iii) fabrication of Cubic Boron Nitride (CBN) grinding wheels, (iv) manufacturing and assembly of automotive cross car beams, and (v) stripping and welding of copper hairpins. Results of the inventories and the LCA will help define parameters for a digital decision-making tool, integrable with CAD programs, to aid the partners in optimizing process chains, ensuring product quality, and minimizing environmental impacts.

2. SCOPE OF THE DOCUMENT

This document develops the complete inventories for the five use cases of FLASH and provides preliminary results for the environmental impacts of each use case, comparing it with conventional technologies.



3. GOAL AND SCOPE DEFINITION

This task aims to develop a complete inventory of environmental relevant data sets for all life cycle stages of the current and the proposed laser technologies, based on the target use cases of FLASH.

CASE STUDY 1 – Acetabular cup (DePuy Synthes)

Characterization of the system to model

Goal: environmental impact assessment for an acetabular cup- compare conventional manufacturing with FLASH laser system.

- Substitute CNC machining (turning, milling of anti-rotational slots, drilling of holes) with laser-based processing.
- An additional scenario is modelled, where additive manufacturing is used to replace the conventional manufacturing of the titanium piece.

System boundaries: from raw materials extraction to manufacturing gate.

Functional unit: Manufacturing of 1 acetabular cup.

Table 1. Main differences between conventional and laser scenarios to analyse in the acetabular cup use case.

Main differences between scenarios to analyse	
Conventional process	Laser process
Turning of anti-rotational slots made with CNC machining	Water jet guided laser + short pulse laser for the anti-rotational slots
Drilling holes with CNC machining	Drilling holes with FLASH laser (CW laser trepan drilling and Ns laser ablation)
-	Surfacing of features, inner and outer area

CASE STUDY 2 – Grinding wheels (Diamoutils SA)

Characterization of the system to model

Goal: environmental impact assessment for the manufacturing of a Cubic Boron Nitride (CBN) grinding wheel – comparison of an electroplated grinding wheel with a laser-processed grinding wheel.

- Substitute galvanic electroplating for the attachment of abrasive materials to a pre-formed wheel hub with laser processing.
- Flash laser will eliminate polluting chemicals used in the electroplating process.

System boundaries: from raw materials extraction to manufacturing gate.

Functional unit: Manufacturing of 1 CBN grinding wheel.



Table 2. Main differences between conventional and laser scenarios to analyse in the grinding wheel use case.

Main differences between scenarios to analyse	
Conventional process	Laser process
Attachment of the abrasive materials using galvanic electroplating Sintering	Precision machining of the wheel hub and machining of abrasive location sites.
	Laser profiling of abrasive shapes, machining of material removal paths and precision truing and dressing of wheel profiles
	Laser marking of identifiers on the produced wheels.

CASE STUDY 3 – Microdrills (Diamoutils SA)

Characterization of the system to model

Goal: environmental impact assessment for the manufacturing of a tungsten carbide (WC) polycrystalline diamond (PCD) micro drill – comparison of CNC-Electro Discharge Grinding (EDG) processed microdrill with a laser-processed micro drill.

- Substitute EDG with laser processes (water jet guided laser and other laser sources).
- Flash laser-based processing could reduce waste by up to 20%, whilst delivering micro-drills with a longer lifetime.

System boundaries: from raw materials extraction to manufacturing gate.

Functional unit: Manufacturing of 1 WC-PCD microdrill.

Table 3. Main differences between conventional and laser scenarios to analyse in the microdrill use case.

Main differences between scenarios to analyse	
Conventional process	Laser process
Shank profile is machined by multi-axis and multi-stage CNC-Electro machining	Shank profile is machined with laser processes: laser cutting, WJG laser, laser surfacing.

CASE STUDY 4 – Cross Car Beam (TOFAS)

Characterization of the system to model

Goal: environmental impact assessment of the Cross Car Beam (CCB) for an EV– comparison of a steel CCB using CNC machining with a steel and aluminium CCB using laser processes.

- Substitute robotic welding and manual projection welding with laser welding (1070 nm CW and 532 nm ns pulsed laser).
- Substitute the steel tubes with aluminum tubes.
- This substitution can enable a weight saving of 1.5 kg and process energy saving up to 65%.



System boundaries: from raw materials extraction to manufacturing gate.

Functional unit: Manufacturing 1 cross-car beam (CCB).

Table 4. Main differences between conventional and laser scenarios to analyse in the cross car beam use case.

Main differences between scenarios to analyse	
Conventional process	Laser process
Roll forming of steel tubes	Aluminum tubes will be used instead of steel
Robotic welding using Gas Melt Arc Welding	Laser welding using a combination of 1070 nm CW and 532 nm ns pulsed laser.

CASE STUDY 5 – Preparation and joining of copper (ATOP)

Characterization of the system to model

Goal: environmental impact assessment of the preparation and joining of copper hairpins– comparison of hairpin stripping done with mechanical milling, hairpin joining made with fiber laser welding with hairpin stripping and joining made with a multi-step hybrid laser.

- Substitute mechanical milling used for hairpin stripping with a millisecond 1070 nm laser
- Substitute hairpin joining done with fibre laser welding (1030-1070 nm) with a 532nm laser and then a 1070nm QCW millisecond.
- As a consequence of an improvement in laser absorption from ~5% to ~40% a drop in average power to 2kW from 4-8kW is expected and an improvement in weld depth will result in **a reduction of scrappage by 25% and a reduction in energy consumption by 60%.**

System boundaries: from raw materials extraction to manufacturing gate.

Functional unit: Processing copper hairpins required for an EV motor using stripping and joining processes

Table 5. Main differences between conventional and laser scenarios to analyse in the copper hairpins stripping and joining use case.

Main differences between scenarios to analyse	
Conventional process	Laser process
Roll forming of steel tubes	Aluminum tubes will be used instead of steel
Robotic welding using Gas Melt Arc Welding	Laser welding using a combination of 1070 nm CW and 532 nm ns pulsed laser.

4. LIFE CYCLE INVENTORY AND COLLECTED DATA

The goal and scope definition also allowed the preparation of the life cycle inventory (LCI) templates for the data collection process, specific for each use case to model. The data collection relied on information provided by the use case partners, Ecoinvent database (selected processes and inputs/outputs in SimaPro), literature review and, in the last case, dummy or unreliable data. The literature review enabled to get knowledge about conventional treatment steps and other life cycle stages, and to obtain reference values of LCI (materials and energy consumption, produced wastes – combined with Ecoinvent information) and LCA of certain stages, which can be useful to compare in a future analysis.

The developed LCI tables and the figures with the first version of LCA modelling in SimaPro for each use case, both for conventional and laser processes and considering the defined functional unit life cycle, are presented in Annex I and Annex II, respectively. The data for packaging and distribution was not considered, since the destinations can significantly vary.

Case study 1: acetabular cup

For a complete representation of this case study, the conventional scenario included the data related to raw materials extraction for titanium, the production (machining) of the titanium alloy piece and the titanium POROCOAT, the manufacturing of the acetabular cup, which consists in four conventional machining steps: mill turning, coating, turning and laser marking.

For the laser scenario, data until the titanium production was identical to the conventional scenario, with the last step of the acetabular cup manufacturing consisting in the following steps: laser cutting of the workpiece and of the anti-rotational slots, laser drilling of holes, surfacing of the workpiece, and laser marking. To calculate the energy consumption of these steps, parameters of the FLASH system were provided by the partners, that indicated the power of each step and the average process time.

An additional scenario was modelled, in which the manufacturing of the components (titanium) is made with additive manufacturing (AM), requiring less material to produce the same amount of titanium.

Case study 2: grinding wheels

For this case study, the inventory for both scenarios included the data related to raw materials extraction for steel and for cubic boron nitride grains and the manufacturing of the grinding wheel. A sensitivity analysis that considers the use phase and end-of-life was considered, as it is expected a reduction in grinding forces by 10% and extended grinding wheel life by 20% over electroplated wheels through a reduction in clogging, for the grinding of ductile materials. It was considered that the grinding wheel produced through electroplating could machine 800 workpieces throughout its lifetime and the laser GW 960 workpieces.



Case study 3: microdrills

For this case study, the inventory for both scenarios included the data related to raw materials extraction for tungsten carbide and the manufacturing of the microdrill. Like the grinding wheels use case, an analysis of the use phase and the end-of-life was performed, as it is expected to have a higher durability. This percentage is still not specified, so it was assumed an increase in durability of 20%.

Case study 4: cross car beam

For this use case, the inventory for both scenarios included the data related to raw materials extraction for steel and/or aluminium and the manufacturing of the cross-car beam. A separate analysis of the use phase was done. It was considered that laser joining of the dissimilar metals (steel and aluminium), enables a weight saving of 1.5 kg (18%), which represents a 0.1-2km range increase translating to a 45g CO₂/100km increase in per EV range and efficiency. In the process itself, an energy saving of 30% was considered for the laser scenario, by reducing processing time (from 900 seconds to 300 seconds per component) and improving efficiency.

Case study 5: copper hairpins

For this use case, the inventory for both scenarios included the data related to raw materials extraction for copper and PEEK/PAI coating and the manufacturing of the copper hairpins (hairpins stripping and joining). It is expected that the FLASH system increases the processing rate of the stripping of the protective coating from copper hairpins by 300% (from 3 cm²/s to 12 cm²/s) and improves laser absorption (from ~5% to ~40%). As a consequence of the improvement in laser absorption, a reduction in average power from 4-8 kW to 2 kW is expected and an improvement in weld depth will result in a reduction of scrappage by 25% and in energy consumption by 60%.

For the amount of copper hairpins produced, it was considered the amount of copper necessary for an EV motor: about 8.5 kg.

5. LCA RESULTS

The next step after the LCI modelling was to proceed with the environmental impacts calculations and interpretation of results of each use case. LCA analysis was carried out in accordance with the international standards ISO 14040:2006, (ISO., 2006a) and ISO 14044 (ISO., 2006b). The LCA modelling was carried out using the SimaPro software (version 9.6) with Ecoinvent 3 as database and ReCiPe 2016 as method of analysis (18 midpoint impact categories i.e. Huijbregts *et al.*, 2016)). For this analysis, global warming potential (GWP), toxicity, mineral resource scarcity (MRS) and water consumption were the categories considered relevant.

Case study 1: acetabular cup

Error! Reference source not found. displays the LCA results per impact category for the three different production scenarios of the acetabular cup.

The results indicate that the laser with AM scenario reduces impacts by approximately 75–80% if compared to the laser and conventional scenarios, in terms of global warming, toxicity, and mineral resource scarcity. This reduction can be attributed to the material efficiency of AM, which requires 82% less titanium to produce the final workpiece compared to the laser and conventional scenarios.

From the laser to the conventional scenario the reduction in GWP is about 2% only, 0% for toxicity and MRS and a 3% reduction in water consumption.

The results show that although laser processing can reduce energy consumption and operating time for key features (holes, anti-rotational slots, surface conditioning), significant improvements to the overall life cycle can only be achieved by changes in the manufacturing technology of the alloy piece, namely with AM processes.

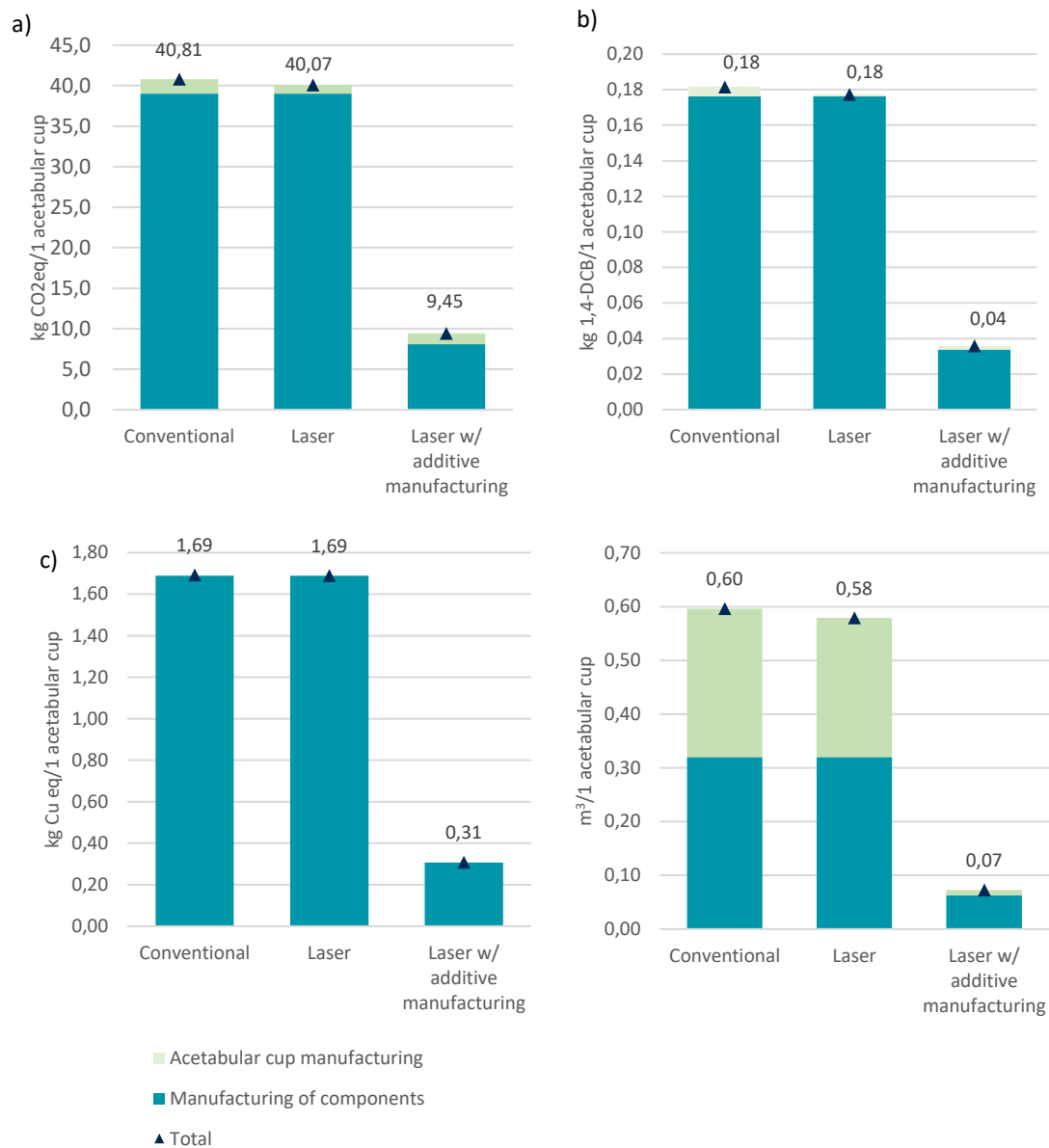


Figure 1. Environmental impacts for each impact category per functional unit for the acetabular cup: a) Global Warming Potential, b) Toxicity, c) Mineral resource scarcity, d) Water consumption.

Another analysis was made, to see out of the processes FLASH substitutes, which are the ones that contribute the most to environmental impacts and compare them to the conventional processes (Figure 2), excluding titanium production.

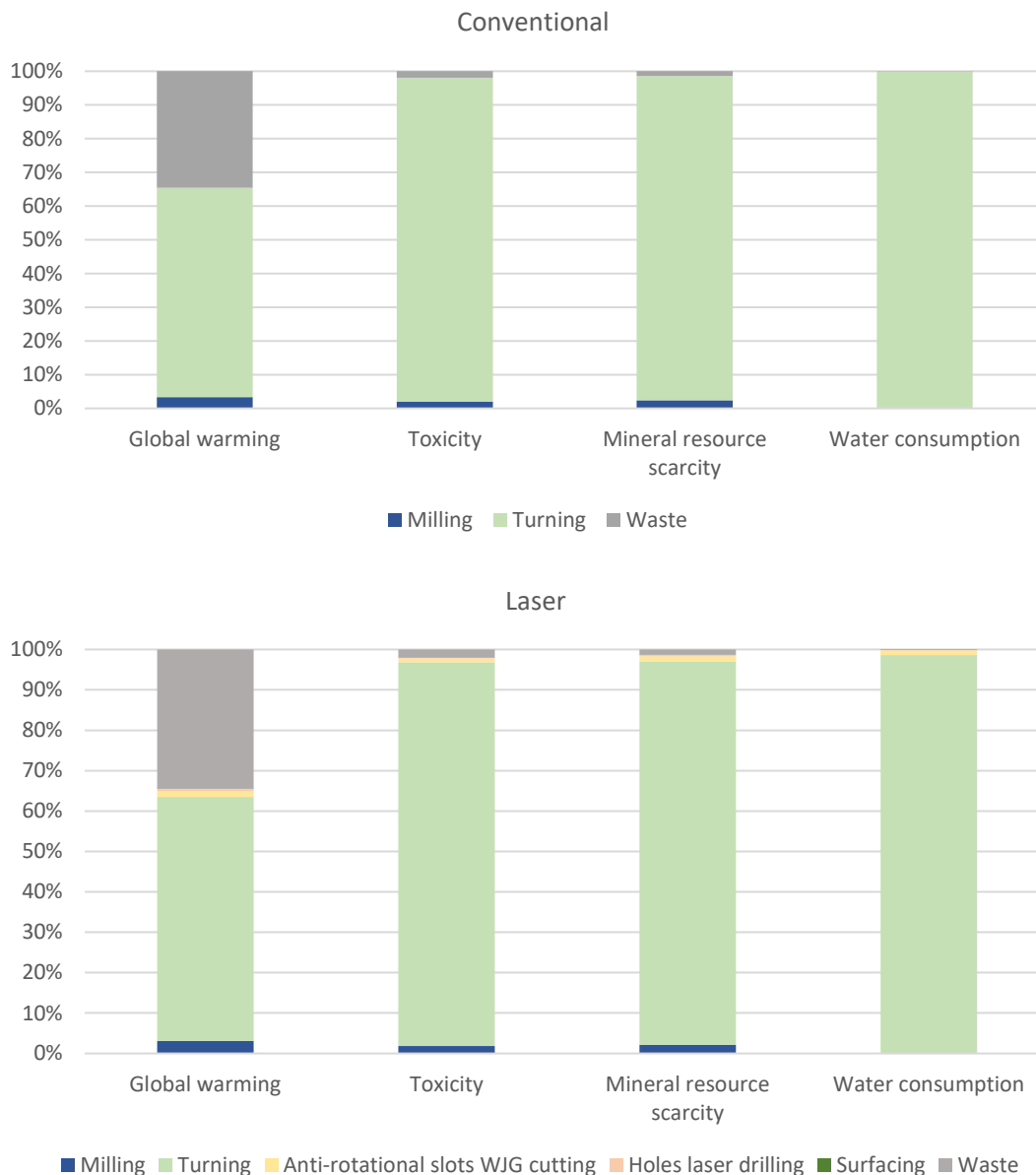


Figure 2. Contribution to overall environmental impacts per process for the acetabular cup: conventional vs. laser.

Milling and turning processes involving CNC machining are used in both the conventional and laser scenarios. The main difference in the laser scenarios is that some features are instead produced by laser processes, amounting for around 3% of the overall material removal. Since the full extent of substitution of conventional processes is still not fully finalised, it is assumed that these processes are still used for the remaining 97% of material removed. We see that for the conventional scenario, the process which is contributing the most to overall environmental impacts is turning, with waste (mostly from lubricants waste) contributing with more than 30% to the GWP. For the laser scenario the outcome is similar and the step that is contributing the most to environmental impacts is the workpiece turning, as it's where the most energy is being consumed (most of the mass is removed in this step). The



contribution of the processes substituted by laser is relatively low (about 2%), as the FLASH laser is removing about 3% of the material only.

Case study 2: grinding wheels

For the second case study, the LCA results for the manufacturing of grinding wheels for both scenarios are seen in **Error! Reference source not found.**

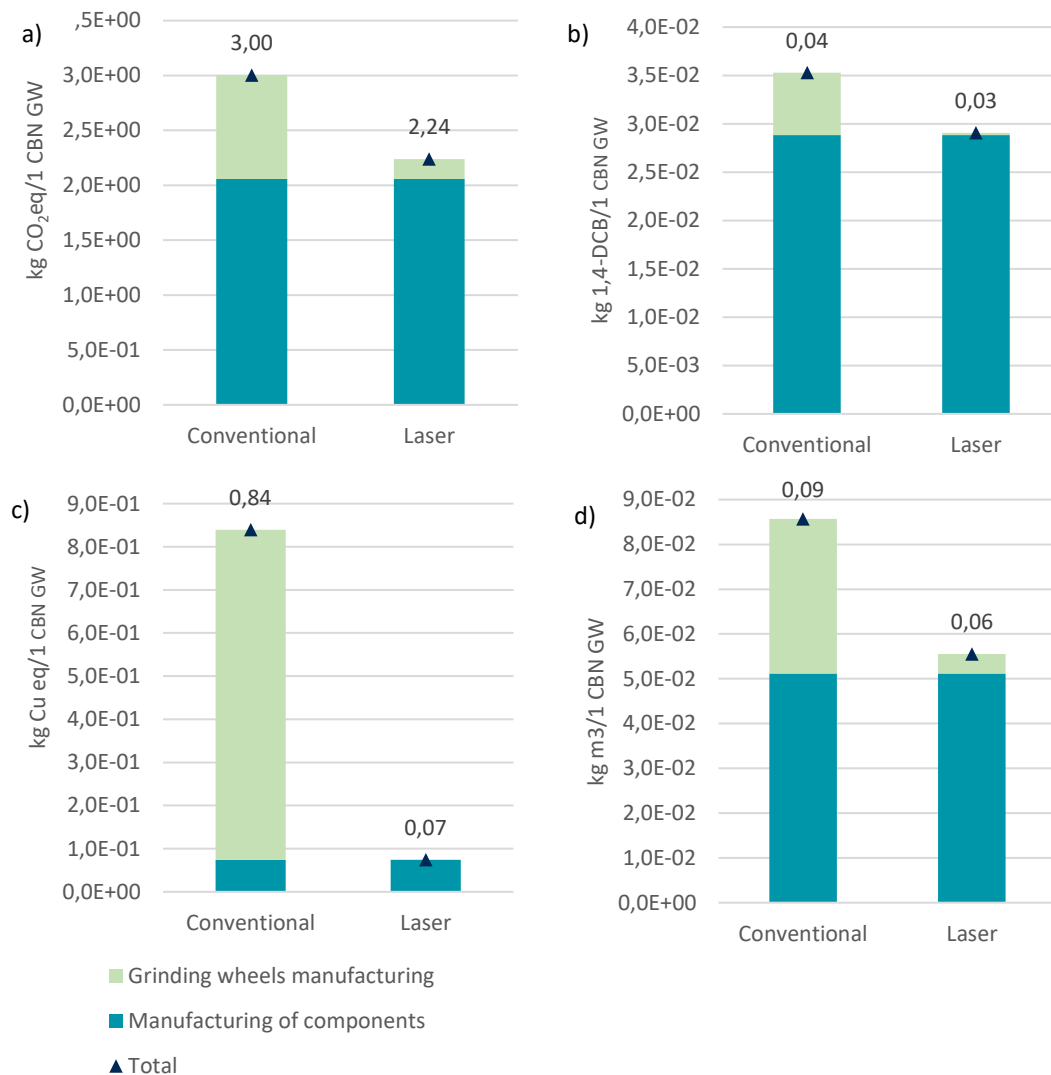


Figure 3. Environmental impacts for each impact category per functional unit for the grinding wheel production: a) Global Warming Potential, b) Toxicity, c) Mineral resource scarcity, d) Water consumption.

The laser scenario has a 40% lower global warming potential, a 15% lower toxicity, 92% lower MRS and 33% lower water consumption than the conventional scenario. This difference is given because in the conventional scenario electroplating is used for the deposition of the CBN on the hub, which uses chemicals such as nickel and sulfuric acid that have a high



environmental impact. Conversely, laser processing needs water (water jet guided laser) and argon, but their impact is much lower.

The mineral resource scarcity in the conventional scenario is two orders of magnitude higher than that of the laser one due to a reduction in the grinding wheels manufacturing step. Although the steel scrap is fully recyclable, reducing the impact for both scenarios, the use of nickel in the electroplating process contributes to a significantly higher value of MRS for the conventional scenario.

Similar to what was done in the previous use case, an analysis of the contribution of each process (excluding raw materials production) to the overall environmental impacts was performed (Figure 4).

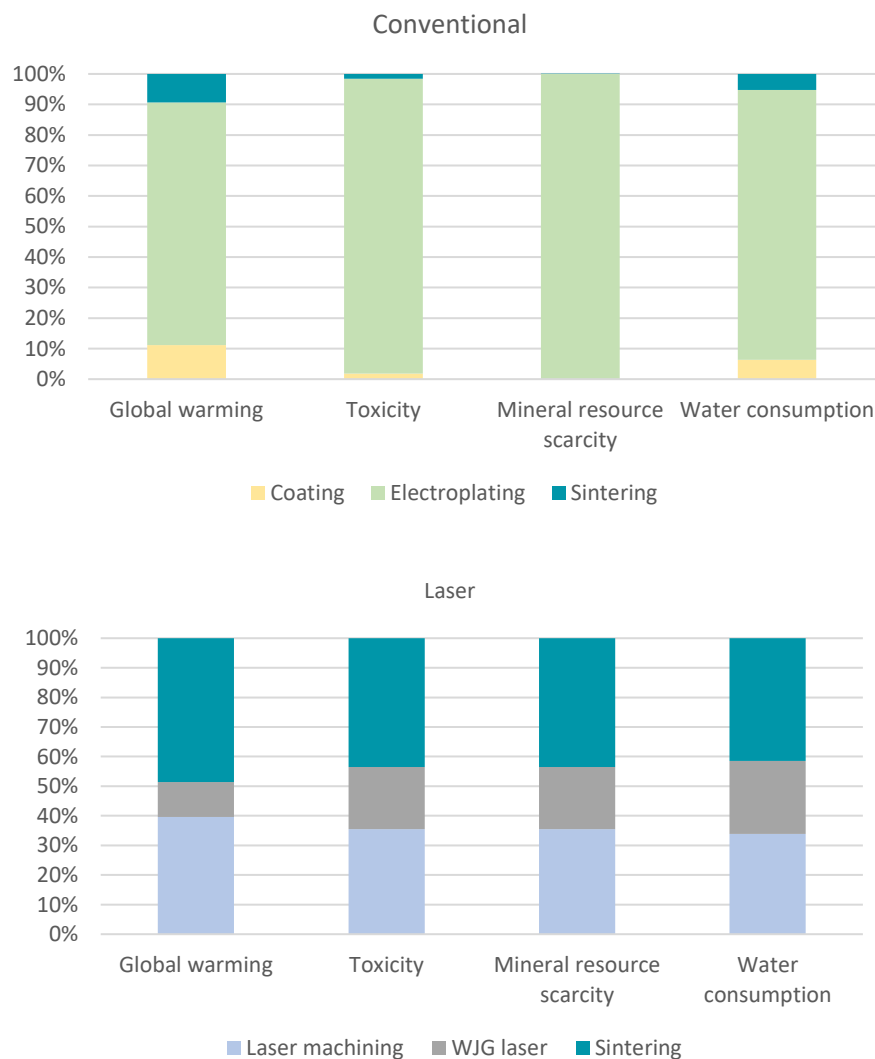


Figure 4. Contribution to overall environmental impacts per process for the grinding wheel: conventional vs. laser.

The sintering process is the same in the conventional and laser scenarios. The processes substituted by FLASH laser have a contribution of just over 50% to overall environmental impacts, with sintering having just below 50%. For the conventional scenario, the electroplating process has the highest contribution to overall impacts (more than 90%).



As the laser processes are expected to contribute to a better performance of the grinding wheels during the use phase, a sensitivity analysis is made to evaluate the environmental performance in the whole-life cycle (Figure 5). The functional unit for this analysis is the machining of 1 workpiece using a grinding wheel.

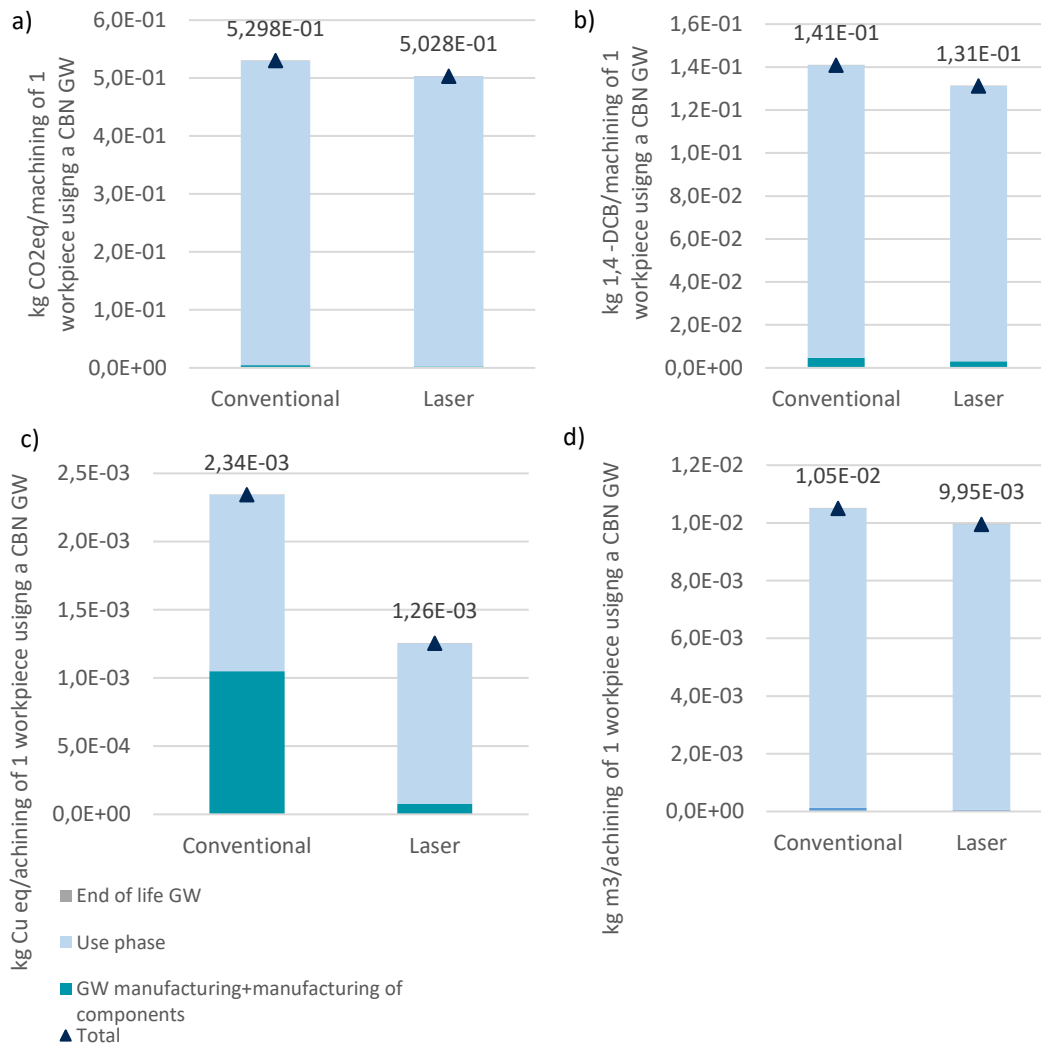


Figure 5. Environmental impacts for each impact category per functional unit for the grinding wheel: a) Global Warming Potential, b) Toxicity, c) Mineral resource scarcity, d) Water consumption.

The use phase is the highest contributor for overall environmental impacts. The laser scenario has a 6% lower global warming potential, a 7% lower toxicity and a 5% lower water consumption than the conventional scenario. This is mainly due to the extended durability of the FLASH grinding wheel. The bigger difference in the MRS category is due to the use of nickel and other chemicals in the conventional scenario in the manufacturing of the grinding wheel.

Case study 3: microdrills



For the microdrills, a similar approach to the grinding wheels was performed. Figure 6 shows the environmental impacts for the production of one microdrill for the conventional and laser scenarios.

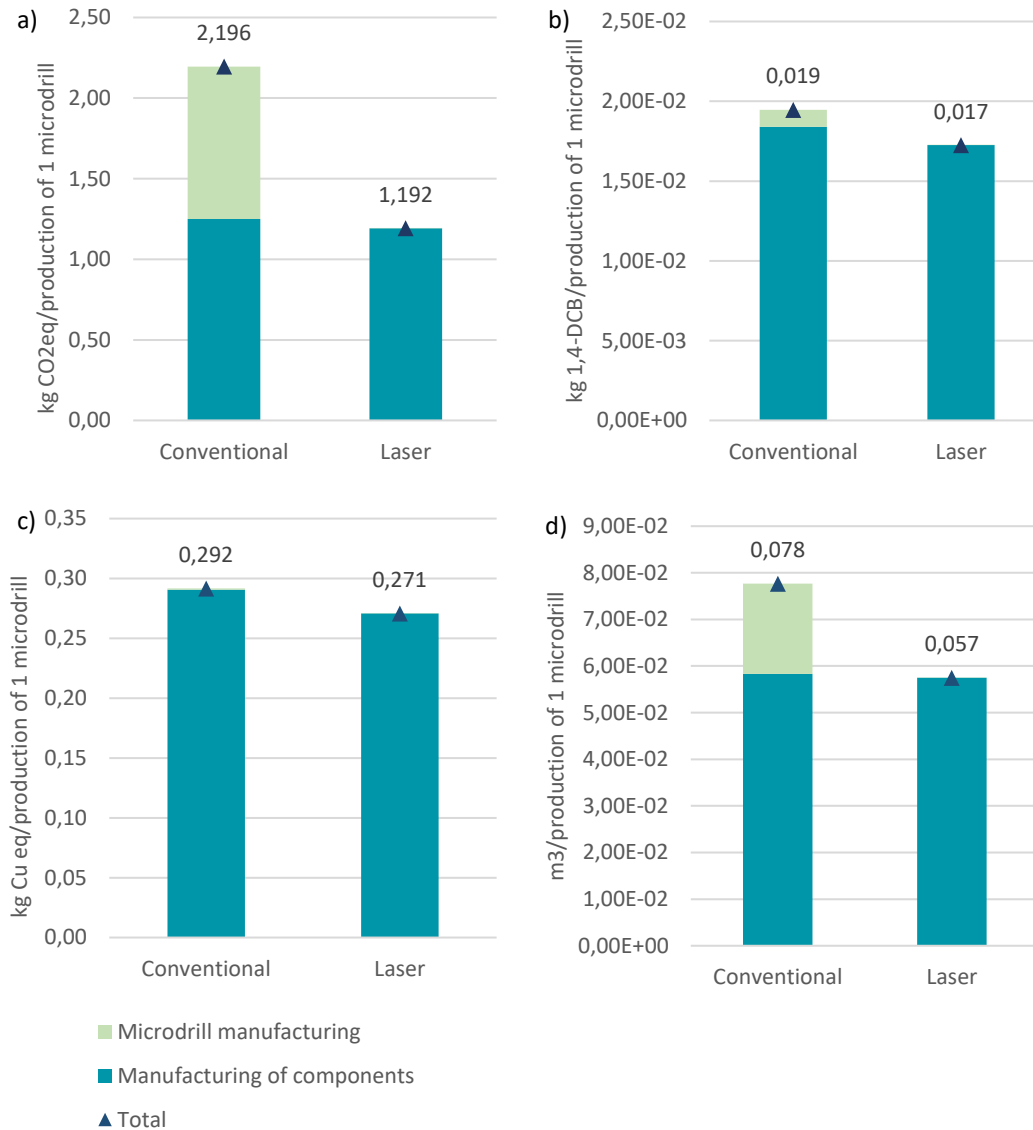


Figure 6. Environmental impacts for each impact category per functional unit for the microdrill production: a) Global Warming Potential, b) Toxicity, c) Mineral resource scarcity, d) Water consumption.

The laser processed microdrill shows a reduction in all impact categories when compared to the conventional scenario. The microdrill manufacturing step has a reduction of 85% and 37% in impacts for GWP and water consumption, respectively. The reduction in energy consumption and reduction of waste of about 20% is what is causing the main difference in results.

Similar to what was done previously, an analysis of the contribution of each process (excluding raw materials production) to the overall environmental impacts was performed (Figure 7). For this use case, data was more difficult to gather as there is less literature, so it was not possible to disaggregate the different steps of the manufacturing of the product. The



processes were divided into production of the material and waste from the processes, which corresponds to inert material (mainly carbide shanks scrap) sent to landfill.



Figure 7. Contribution to overall environmental impacts per process for the microdrill: conventional vs. laser.

The LCA results for the whole-life cycle for the two scenarios considered were analysed (Figure 8), where the functional unit is the machining of 1 workpiece using a microdrill.

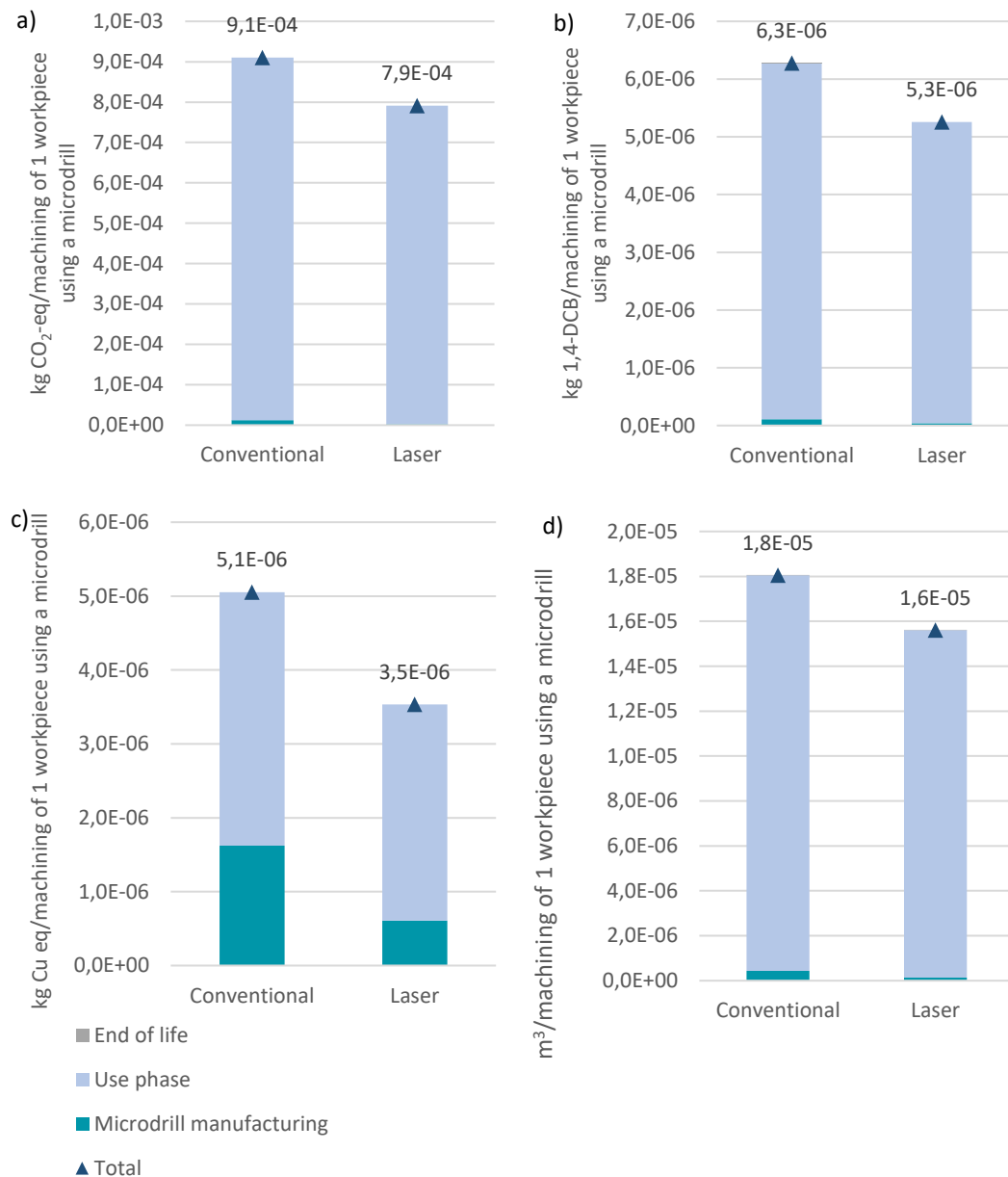


Figure 8. Environmental impacts for each impact category per functional unit for the microdrill (whole life-cycle):
a) Global Warming Potential, b) Toxicity, c) Mineral resource scarcity, d) Water consumption.

The use phase is the highest contributor for overall environmental impacts. There is also a reduction in all impact categories, with a more pronounced decrease in the MRS category (about 32% reduction). The overall decrease is because the FLASH processed microdrill has 20% higher durability when compared to the conventional one.

Case study 4: cross car beam

For the cross-car beam, an analysis of the production of the beam for both scenarios was done (Figure 9).

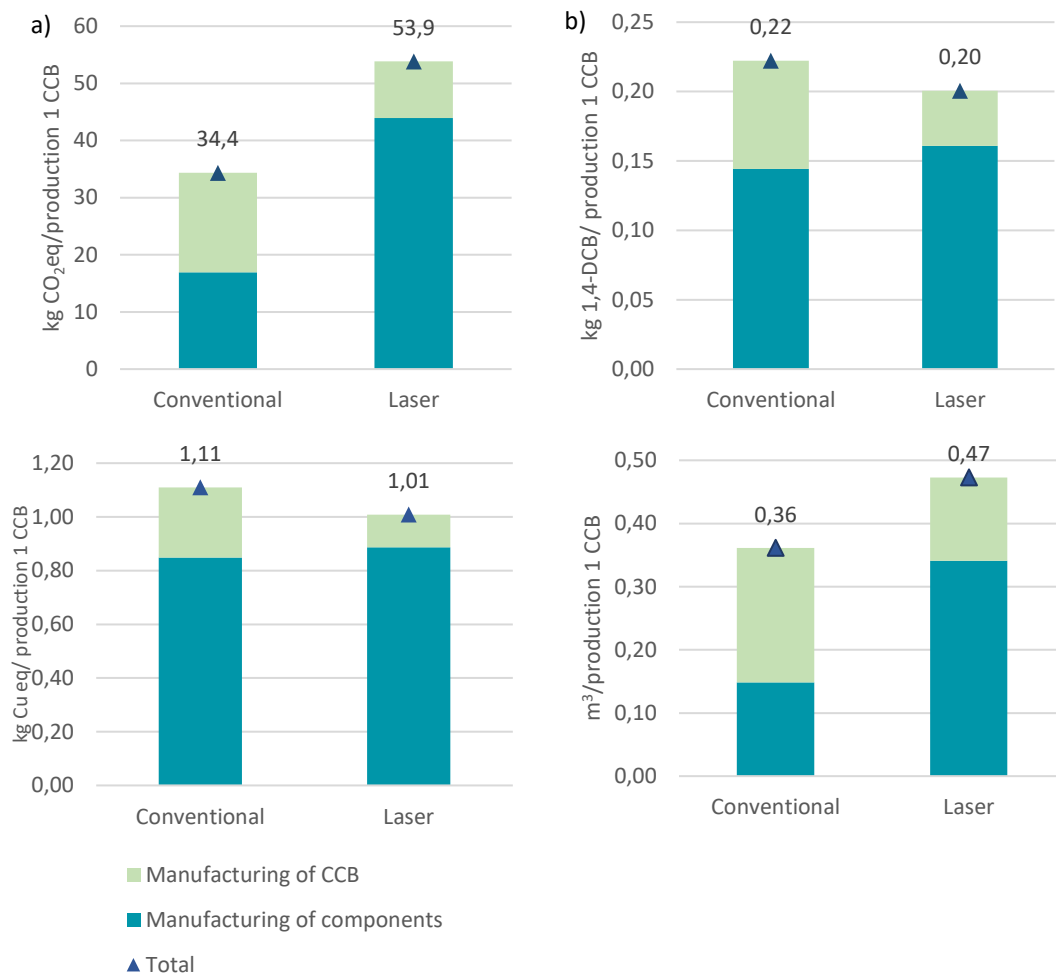


Figure 9. Environmental impacts for each impact category per functional unit for the CCB production: a) Global Warming Potential, b) Toxicity, c) Mineral resource scarcity, d) Water consumption.

For this use case, the laser scenario presents higher environmental impacts for GWP and water consumption. The laser welded cross car beam presented a 56% higher GWP, due to the aluminium production, which presents a higher carbon footprint than steel. However, it's clear that the manufacturing of the CCB production itself has a clear reduction in all impact categories, due to a reduction in energy consumption. For toxicity and MRS there was reduction of about 9% for both categories from the conventional scenario to the laser scenario.

It is important to look at the contributions per process/material for both scenarios to better understand their main differences (Figure 10).

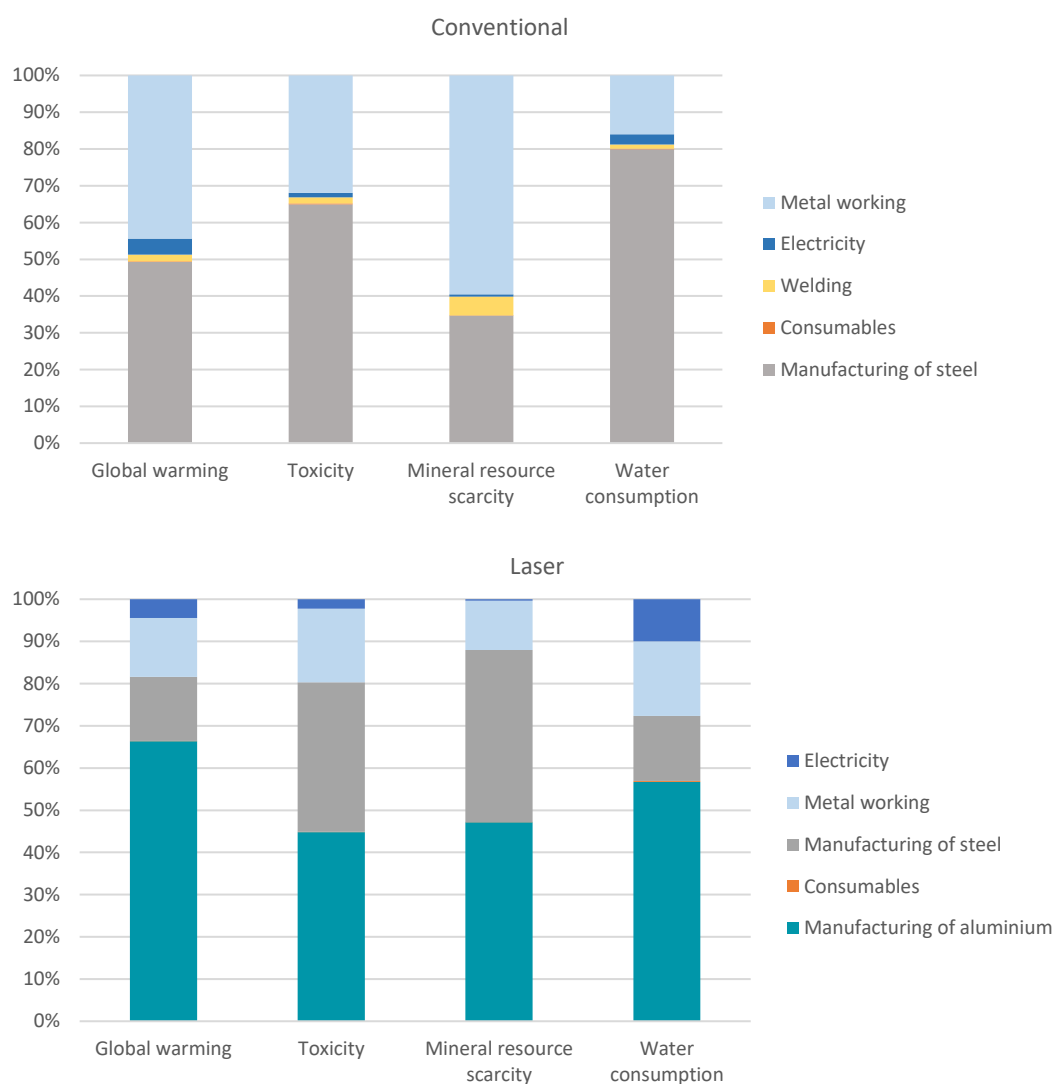


Figure 10. Contribution to overall environmental impacts per process/material for the CCB: conventional vs. laser.

Although the laser processed beam is 1.5 kg lighter than the steel CCB, the aluminium manufacturing dominates the overall impacts in the laser scenario (more than 60% for GWP), whereas the steel contributes about 15% to the GWP. Besides this, the electricity consumption in the laser scenario is higher than the conventional one, having a higher contribution to overall environmental impacts.

Similar to the use cases for the machining tools, a sensitivity analysis considering the use phase and end-of-life of the CCB was performed. When the use phase of the CCB is considered, the scenario shifts, as seen in Figure 11. For the use phase of the laser CCB, two scenarios were tested: one where the range of the EV increased 0.1 km, and another where the range increased 2 km. The results presented are relative to the mass percentage of the CCB in the vehicle and for the vehicle lifetime (assumed 150 000 km).

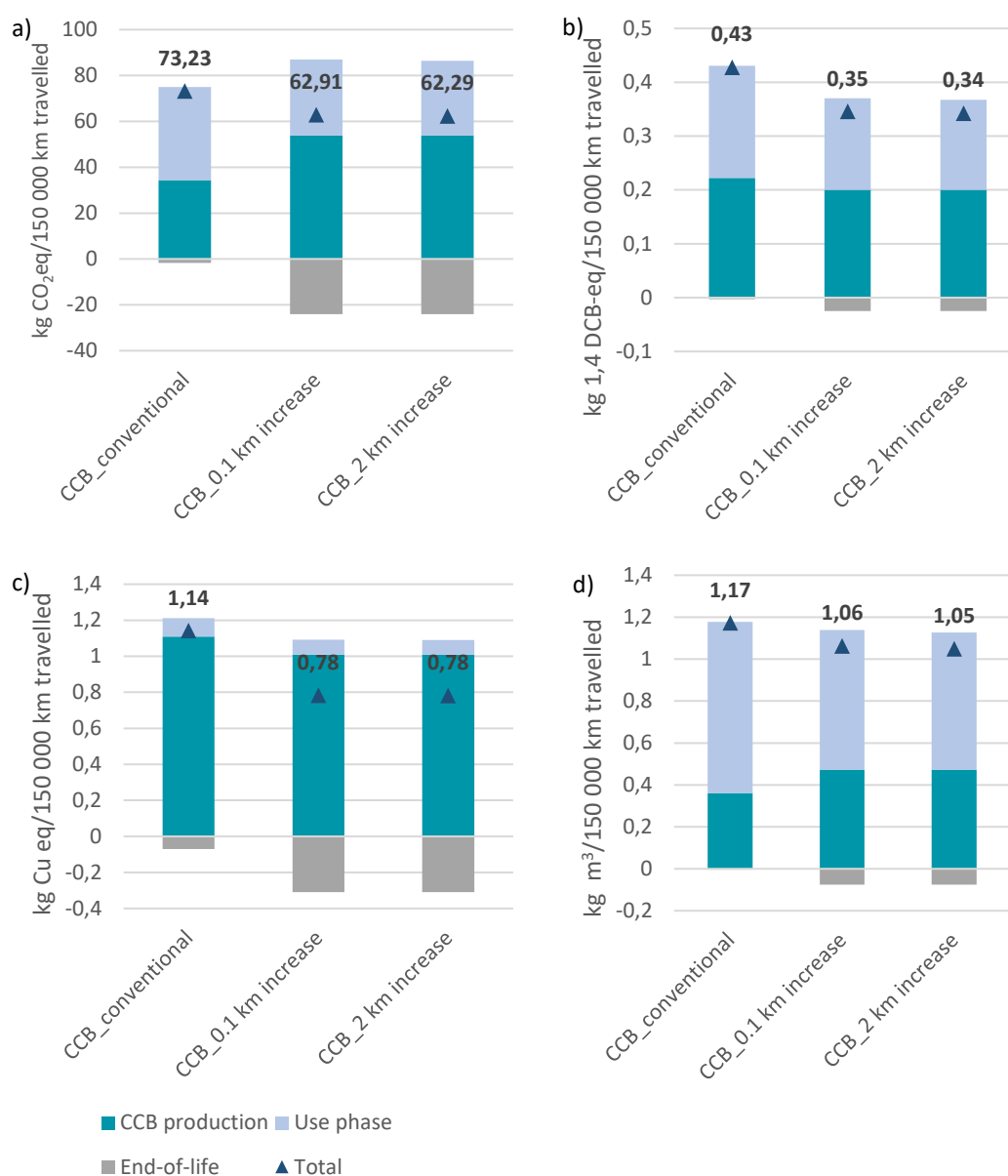


Figure 11. Environmental impacts for each impact category per functional unit for the CCB (full life-cycle): a) Global Warming Potential, b) Toxicity, c) Mineral resource scarcity, d) Water consumption.

The CCB laser presents a lower environmental impact for all impact categories for both ranges. In terms of GWP, there is saving of 10.3 kg of CO₂eq per 150 000 km travelled (relative to the mass % of the CCB – about 0.5% of the whole mass of the vehicle). The negative value of the end-of-life is given due to the benefit of recycling of CCB.



Case study 5: copper hairpins

For the copper hairpins use case, the production environmental impacts for both scenarios were analysed (Figure 12).

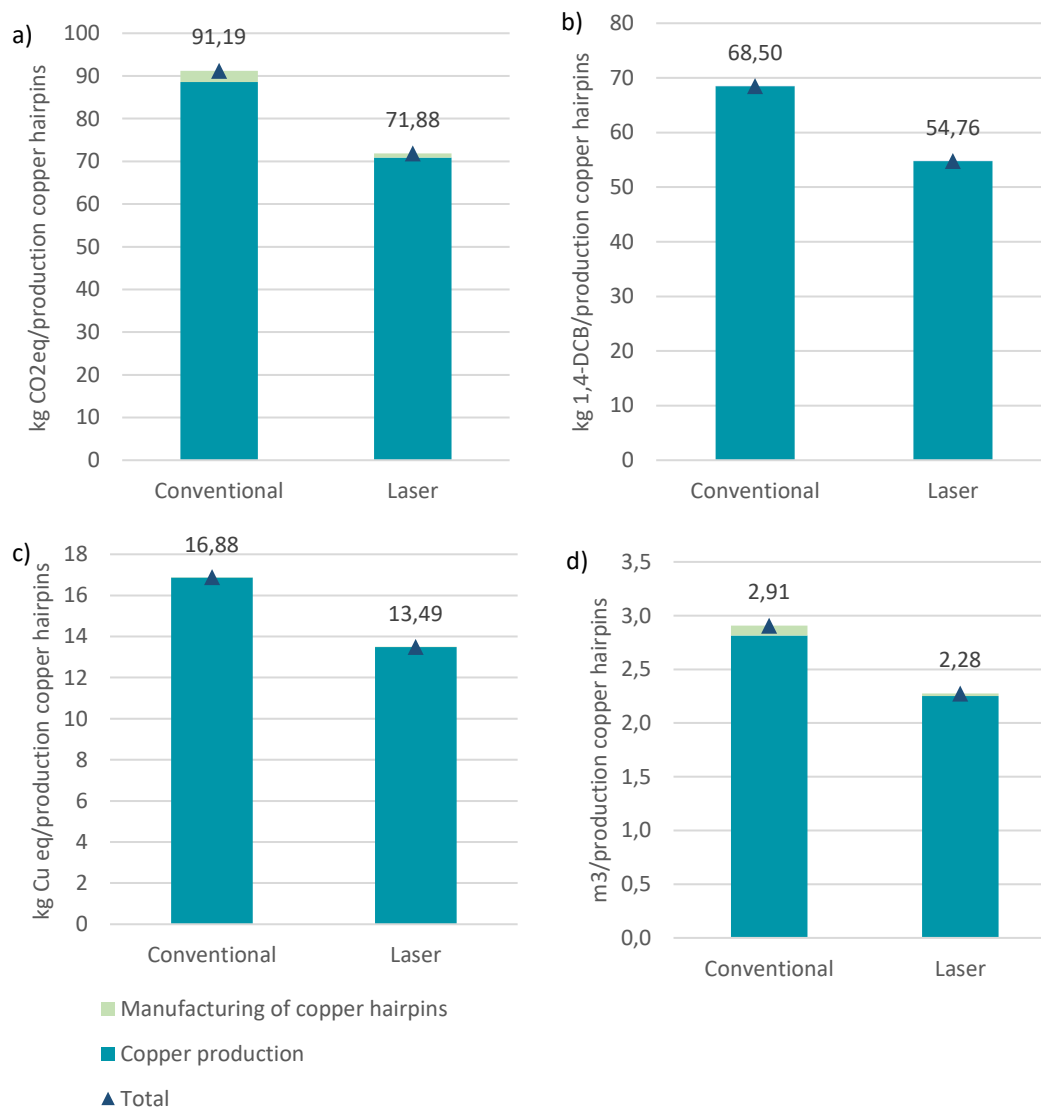


Figure 12. Environmental impacts for each impact category per functional unit for the copper hairpins: a) Global Warming Potential, b) Toxicity, c) Mineral resource scarcity, d) Water consumption.

The results show that the FLASH processed copper hairpins have a lower environmental impact in all impact categories, having a reduction of about 27% in GWP. This is mainly due to the need for less copper for the laser scenario, since the process produces 20% less scrapage. From the results, it's clear that copper production has the highest contribution for overall environmental impacts.

The lower energy consumption combined with the lower raw material amount reduces the environmental impact of FLASH based copper hairpins.

An additional analysis to see the contributions to the overall impacts from each process (Figure 13) was performed (excluding copper production).

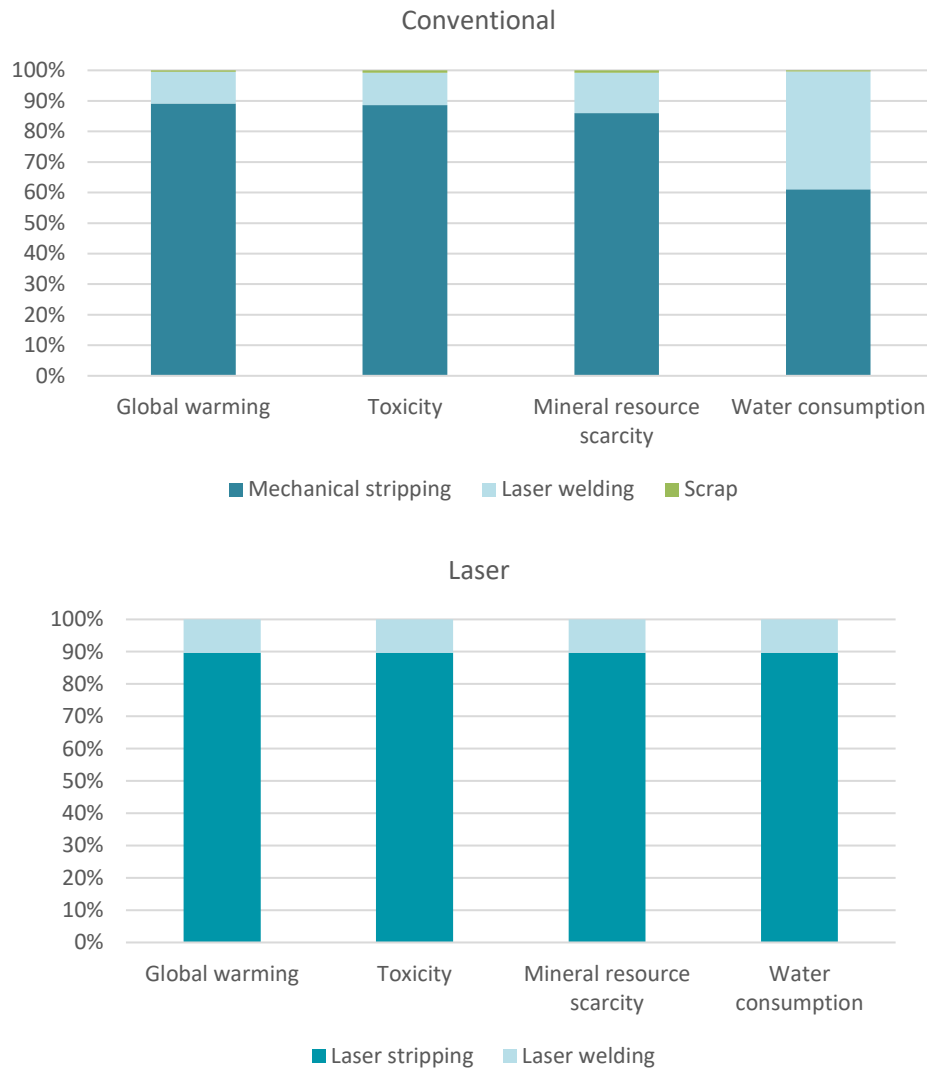


Figure 13. Contribution to overall environmental impacts per process/material for the copper hairpins: conventional vs. laser.

When comparing the contributions of the processes substituted by FLASH, the laser welding has a reduction in contribution to environmental impacts from one scenario to another (from 12% contribution to 10% contribution). For the conventional scenario, the scrap has a negligible contribution to overall impacts. Both for the laser and conventional scenario, stripping is the process that contributes the most to environmental impacts, due to higher energy consumption.

6. CONCLUSIONS

The LCA analysis for the five use cases in the FLASH project was successfully performed based on the available data at this stage of the project. The preliminary results obtained for each case study show that the FLASH laser (water jet guided laser, laser cutting), and the consequent optimization in other life cycle stages, decrease the environmental impacts and improve the sustainability of the studied products along their value chains, with reductions in GWP ranging from 3% (acetabular cup use case) to 85% (microdrills use case).

However, it is necessary to follow up the most recent developments achieved in the case studies and update also initial target scenarios, i.e. fine-tune each life cycle inventory and to substitute critical inputs/outputs that currently rely on dummy data or estimations from literature.

The main advantages of LCA include the possibility to compare environmental impacts of different products with similar function, to identify the environmentally most dominant phases in a product life cycle and to indicate opportunities for improvement (eco-design).

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<https://doi.org/10.1007/s11367-017-1375-y>

Annex I – LCI tables for the use cases

Table 6. Life cycle inventory for the acetabular cup use case: conventional scenario.

Life cycle stage	1. Raw materials extraction				2. Production				3. Acetabular cup manufacturing				References
	Parameter	Unit	Value	Observations	Parameter	Unit	Value	Observations	Parameter	Unit	Value	Observations	
Inputs from technological sphere (materials, water, fuels)	Rutile, 95% titanium dioxide	kg	0.07	Titanium sponge production; Ecoinvent	Ti tetrachloride (Ti6Al4V)	kg	0.83		Ti-6Al-4V alloy piece	kg	0.135	Weight of component required to produce 1 cup	Partners FLASH
	Titania slag, 94% titanium dioxide	kg	0.05	Titanium sponge production; Ecoinvent	Magnesium	kg	0.07		Ti coating (POROCOAT@)	kg	0.001	Weight of material used for the coating step	[1] Surface Finishing of Additive Manufactured Ti-6Al-4V Alloy: A Comparison between Abrasive Fluidized Bed and Laser Finishing; E. Atzeni et al.; Materials (2021)
	Chlorine	kg	0.19	Titanium sponge production; Ecoinvent					Lubricant	kg	0.04		[2] Daniyan, I., Mpofu, K., Bello, K., & Muvunzi, R. (2022). Life cycle assessment for the milling operation of titanium alloy (Ti6Al4V). Procedia CIRP, 105, 811–816. https://doi.org/10.1016/j.procir.2022.02.134 (An estimation was performed as the study used a 45 kg alloy piece)
	Petroleum coke	kg	0.04	Titanium sponge production; Ecoinvent					Coolant (water based)	kg	40.9		[3] Bergs, T., Grünebaum, T., Fricke, K., Barth, S., & Ganser, P. (2021). Life cycle assessment for milling of Ti- and Ni-based alloy aero engine components. Procedia CIRP, 98, 625–630. https://doi.org/10.1016/j.procir.2021.01.165
	Sodium hydroxide	kg	0.30	Titanium sponge production; Ecoinvent					Water	m3	0.26		[4] LCA Comparison of Electroplating and Other Thermal Spray Processes, A. Moign et al., Thermal Spray 2009: Proceedings of the International Thermal Spray Conference, 2009; Surface Finishing of Additive Manufactured Ti-6Al-4V Alloy: A Comparison between Abrasive Fluidized Bed and Laser Finishing; E. Atzeni
	Tap water	kg	0.03	Titanium sponge production; Ecoinvent					Compressed air	kg	54		[3]
Inputs from technological sphere (energy)	Electricity	kWh	0.17	Titanium sponge production; Ecoinvent	Electricity (Kroll process)	kWh	0.32		Electricity (mill turning)	kWh	0.17		[4] Paris, H., Mokhtarian, H., Coatanéa, E., Museau, M., & Ituarte, I. F. (2016). Comparative environmental impacts of additive and subtractive manufacturing technologies. CIRP Annals, 65(1), 29–32. https://doi.org/10.1016/j.cirp.2016.04.036
	Heat	MJ	9.76	Titanium sponge production; Ecoinvent	Electricity (vacuum arc remelting)	kWh	0.14		Electricity (coating)	kWh	0.02		[5] Lyons, R., Newell, A., Ghadimi, P., & Papakostas, N. (2020). Environmental impacts of conventional and additive manufacturing for the production of Ti-6Al-4V knee implant: a life cycle approach. The International Journal of Advanced Manufacturing Technology, 112(3-4), 787–801. https://doi.org/10.1007/s00170-020-06367-7
					Electricity (forging workpiece)	kWh	0.54		Electricity (turning)	kWh	1.91		[5]
					Electricity (atomisation)	kWh	0.01		Electricity (laser marking)	kWh	0.042		[6] https://www.linxuanlaser.com/does-the-laser-marking-machine-consume-electricity/#:~:text=Generally%2C%20the%20power%20of%20a,on%20the%20local%20electricity%20bill.
Outputs (wastes, emissions)	Carbon dioxide	kg	0.03	Titanium sponge production; Ecoinvent	Inert waste	kg	0.005		Ti-6Al-4V alloy piece	kg	0.085	The final weight of the workpiece is about 45 grams	
	Carbon monoxide	kg	0.04	Titanium sponge production; Ecoinvent	Magnesium chloride	kg	0.25		Ti coating	kg	2.00E-04	Waste material from the coating	[7] Environmental sustainability of orthopedic devices produced with powder bed fusion, G. Cappucci et al., Journal of Industrial Ecology, 2020



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	Basic oxygen furnace slag	kg	0.30	Titanium sponge production; Ecoinvent					Waste lubricant	kg	0.04		This value was estimated from the study (45 kg of titanium generate 12 kg of waste lubricant and 1.01 generate x) [2]
	Wastewater	kg	0.00003	Titanium sponge production; Ecoinvent									

Table 7. Life cycle inventory for the acetabular cup use case: laser scenario.

Life cycle stage	1. Raw materials extraction				2. Production				3. Acetabular cup manufacturing			
	Parameter	Unit	Value	Observations	Parameter	Unit	Value	Observations	Parameter	Unit	Value	Observations
Inputs from technological sphere (materials, water, fuels)	Rutile, 95% titanium dioxide	kg	0.07	0,48 kg/kg of Ti workpiece + Ti coating Source: Ecoinvent	Ti tetrachloride (Ti6Al4V)	kg	0.8272	6.1 kg/kg of Ti workpiece + Ti coating	Ti-6Al-4V alloy piece	kg	0.13460717	Weight of component required to produce 1 cup Source: Partners
	Titania slag, 94% titanium dioxide	kg	0.05	0,37 kg/kg of Ti workpiece + Ti coating Source: Ecoinvent	Magnesium	kg	0.07	0,49 kg/kg of Ti Workpiece + Ti coating Source: Ecoinvent	Ti coating (POROCOAT@)	kg	0.001	Weight of material used for the coating step Source: Partners
	Chlorine	kg	0.19	1,43 kg/kg of Ti workpiece + Ti coating Source: Ecoinvent				To take into account the material efficiency of conventional manufacturing, it was considered that the process to obtain 1.01 kg of titanium had an efficiency of 16%. This means that to produce 1.01 kg of titanium, 6.1 kg of titanium sponge are necessary. This information was taken from: Environmental impacts of conventional and additive manufacturing for the production of Ti-6Al-4V knee implant: A life cycle approach. Lyons, R. et al., The International Journal of Advanced Manufacturing Technology, 2020	Water	kg	2.91	Source: Partners
	Petroleum coke	kg	0.04	0,31 kg/kg of Ti workpiece + Ti coating Source: Ecoinvent					Inert gas (Helium)	L	68.52	Source: Partners
	Sodium hydroxide	kg	0.30	2,18 kg/kg of Ti workpiece + Ti coating Source: Ecoinvent					Argon	L	2.34	Source: Partners



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	Tap water	kg	0.03	0,21 kg/kg of Ti workpiece + Ti coating Source: Ecoinvent								
Inputs from technological sphere (energy)	Electricity	kWh	0.165	1,22 kWh/kg of Ti workpiece + Ti coating Source: Ecoinvent	Electricity (Kroll process)	kWh	0.32	2.33 kWh/kg of Ti workpiece + Ti coating Source: Ecoinvent	Electricity (mill turning)	kWh	0.17	[5]
	Electricity	kWh	0.165	1,22 kWh/kg of Ti workpiece + Ti coating Source: Ecoinvent	Electricity (Kroll process)	kWh	0.32	2.33 kWh/kg of Ti workpiece + Ti coating Source: Ecoinvent	Electricity (Cutting - 2 step long pulse / second stage water jet)	kWh	1.77	[5]
	Heat	MJ	9.76	71,97 MJ/kg of Ti workpiece + Ti coating Source: Ecoinvent	Electricity (vacuum arc remelting)	kWh	0.1356	1 kWh/kg of Ti Workpiece + Ti coating Source: Ecoinvent	Electricity (Milling - anti-rotational slots / water jet)	kWh	0.08	Estimated from partners data
					Electricity (forging workpiece)	kWh	0.5425	4,03 kWh/kg of Ti workpiece [5]	Electricity (coating)	kWh	0.02	[5]
					Electricity (atomisation)	kWh	0.01	8.81 kWh/kg of Ti coating [5]	Electricity (Surfacing - short pulse)	kWh	0.00141799	Source: MTC (Surfacing of external, internal area and anti-rotational slots)
									Electricity (Laser marking- short pulse)	kWh	0.042	[6]
Outputs (wastes, emissions)	Carbon dioxide	kg	0.031	0,23 kg/kg of Ti workpiece + Ti coating Source: Ecoinvent	Inert waste	kg	0.0054	0,04 kg/kg of Ti workpiece + Ti coating Source: Ecoinvent	Electricity (Cutting Hole profile 1)	kWh	0.001	Source: MTC
	Carbon monoxide	kg	0.039	0,29 kg/kg of Ti workpiece + Ti coating Source: Ecoinvent	Magnesium chloride	kg	0.25	1,87 kg/kg of Ti workpiece + Ti coating Source: Ecoinvent	Electricity (Cutting Hole profile 2)	kWh	0.008	Source: MTC
	Basic oxygen furnace slag	kg	0.301	2,22 kg/kg of Ti workpiece + Ti coating Source: Ecoinvent					Ti-6Al-4V alloy piece	kg	0.084	The final weight of the cup is 49.87 grams



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	Wastewater	kg	3E-05	0,0002 kg/kg of Ti workpiece + Ti coating Source: Ecoinvent					Wastewater	m3	nil	Consider those as insignificant
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Table 8. Life cycle inventory for the acetabular cup use case: additive manufacturing scenario.

Life cycle stage	1. Raw materials extraction				2. Production				3. Acetabular cup manufacturing			
	Parameter	Unit	Value	Observations	Parameter	Unit	Value	Observations	Parameter	Unit	Value	Observations
Inputs from technological sphere (materials, water, fuels)	Rutile, 95% titanium dioxide	kg	0.07	0,48 kg/kg of Ti workpiece + Ti coating Source: Ecoinvent	Ti tetrachloride (Ti6Al4V)	kg	0.1505	1,11 kg/kg of Ti workpiece + Ti coating Source: Ecoinvent	Ti-6Al-4V alloy piece	kg	0.13460717	Weight of component required to produce 1 cup Source: Partners
	Titania slag, 94% titanium dioxide	kg	0.05	0,37 kg/kg of Ti workpiece + Ti coating Source: Ecoinvent	Magnesium	kg	0.07	0,49 kg/kg of Ti Workpiece + Ti coating Source: Ecoinvent	Ti coating (POROCOAT@)	kg	0.001	Weight of material used for the coating step Source: Partners
	Chlorine	kg	0.19	1,43 kg/kg of Ti workpiece + Ti coating Source: Ecoinvent				To take into account the material efficiency of additive manufacturing, it was considered that the process to obtain 0.135 kg of titanium had an efficiency of 90%. This means that to produce 1.01 kg of titanium, 1.11 kg of titanium sponge are necessary. This information was taken from: Environmental impacts of conventional and additive manufacturing for the production of Ti-6Al-4V knee implant: A life cycle approach. Lyons, R. et al., The International Journal of Advanced Manufacturing Technology, 2020	Water	kg	2.91	Source: Partners
	Petroleum coke	kg	0.04	0,31 kg/kg of Ti workpiece + Ti coating Source: Ecoinvent					Inert gas (Helium)	L	68.52	Source: Partners
	Sodium hydroxide	kg	0.30	2,18 kg/kg of Ti workpiece + Ti coating Source: Ecoinvent					Argon	L	2.34	Source: Partners



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	Tap water	kg	0.03	0,21 kg/kg of Ti workpiece + Ti coating Source: Ecoinvent								
Inputs from technological sphere (energy)	Electricity	kWh	0.165	1,22 kWh/kg of Ti workpiece + Ti coating Source: Ecoinvent	Electricity (vacuum arc remelting)	kWh	0.1356	1 kWh/kg of Ti Workpiece + Ti coating Source: Ecoinvent	Electricity (mill turning)	kWh	2.24	[5]
	Electricity	kWh	0.165	1,22 kWh/kg of Ti workpiece + Ti coating Source: Ecoinvent	Electricity (atomisation)	kWh	0.0088	8.81 kWh/kg of Ti coating [5]	Electricity (Cutting - 2 step long pulse / second stage water jet)	kWh	1.77	[5]
	Heat	MJ	9.76	71,97 MJ/kg of Ti workpiece + Ti coating Source: Ecoinvent	Electricity (additive manufacturing)	kWh	2.2426	16,66 kWh/kg of Ti workpiece [5]	Electricity (Milling - anti-rotational slots / water jet)	kWh	0.08	
									Electricity (coating)	kWh	0.02	Source: Environmental impacts of conventional and additive manufacturing for the production of Ti-6Al-4V knee implant: A life cycle approach. Lyons, R. et al., The International Journal of Advanced Manufacturing Technology, 2020
									Electricity (Surfacing - short pulse)	kWh	0.00141799	Source: MTC (Surfacing of external, internal area and anti-rotational slots)
									Electricity (Laser marking- short pulse)	kWh	0.042	[6]
Outputs (wastes, emissions)	Carbon dioxide	kg	0.031	0,23 kg/kg of Ti workpiece + Ti coating Source: Ecoinvent	Inert waste	kg	0.0054	0,04 kg/kg of Ti workpiece + Ti coating Source: Ecoinvent	Electricity (Cutting Hole profile 1)	kWh	0.001	Source: MTC
	Carbon monoxide	kg	0.039	0,29 kg/kg of Ti workpiece + Ti coating Source: Ecoinvent	Magnesium chloride	kg	0.25	1,87 kg/kg of Ti workpiece + Ti coating Source: Ecoinvent	Electricity (Cutting Hole profile 2)	kWh	0.008	Source: MTC
	Basic oxygen furnace slag	kg	0.301	2,22 kg/kg of Ti workpiece + Ti coating Source: Ecoinvent					Ti-6Al-4V alloy piece	kg	0.084	The final weight of the cup is 49.87 grams
	Wastewater	kg	3E-05	0,0002 kg/kg of Ti					Wastewater	m3	nil	Consider those as insignificant



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				workpiece + Ti coating															
				Source: Ecoinvent															

References:

- [1] Surface Finishing of Additive Manufactured Ti-6Al-4V Alloy: A Comparison between Abrasive Fluidized Bed and Laser Finishing; E. Atzeni et al.; Materials (2021)
- [2] Daniyan, I., Mpofu, K., Bello, K., & Muvunzi, R. (2022). Life cycle assessment for the milling operation of titanium alloy (Ti6Al4V). Procedia CIRP, 105, 811–816. <https://doi.org/10.1016/j.procir.2022.02.134>
- [3] Bergs, T., Grünebaum, T., Fricke, K., Barth, S., & Ganser, P. (2021). Life cycle assessment for milling of Ti- and Ni-based alloy aero engine components. Procedia CIRP, 98, 625–630. <https://doi.org/10.1016/j.procir.2021.01.165>
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- [5] Lyons, R., Newell, A., Ghadimi, P., & Papakostas, N. (2020). Environmental impacts of conventional and additive manufacturing for the production of Ti-6Al-4V knee implant: a life cycle approach. The International Journal of Advanced Manufacturing Technology, 112(3-4), 787–801. <https://doi.org/10.1007/s00170-020-06367-7>
- [6] <https://www.linxuanlaser.com/does-the-laser-marking-machine-consume-electricity/#:~:text=Generally%2C%20the%20power%20of%20a,on%20the%20local%20electricity%20bill.>
- [7] Environmental sustainability of orthopedic devices produced with powder bed fusion, G. Cappucci et al., Journal of Industrial Ecology, 2020



Table 9. Life cycle inventory for the grinding wheel use case: conventional scenario.

Life cycle stage	1. Raw materials extraction				2. Production				3. Grinding wheel manufacturing				4. Use phase			
	Parameter	Unit	Source	Observations	Parameter	Unit	Value	Sources	Parameter	Unit	Value	Source	Parameter	Unit	Value	Source
Inputs from technological sphere (materials, water, fuels)	Aluminium ingot	kg	0.2371872	For steel production 1,88 kg/kg steel Source: Ecoinvent	Steel (low-alloyed, hot rolled)	kg	2.067	For steel hub This value was estimated from [1] Winter, M., Ibbotson, S., Kara, S., & Herrmann, C. (2015). Life cycle assessment of cubic boron nitride grinding wheels. Journal of Cleaner Production, 107, 707–721. https://doi.org/10.1016/j.jclepro.2015.05.088 . The study stated that to produce one steel hub of 1 kg, 17 kg of steel were necessary.	Steel hub	kg	0.126	Weight of steel hub to make one CBN Grinding Wheel The total weight of the workpiece (coating+steel hub) was estimated to be 0.13 kg. The dimensions of the GW are 100mm x 10 mm. A standard commercial GW with dimensions of 203.2mm x 38.1 mm has a weight of 2.04 kg. The volume of each workpiece was calculated, and an estimation was performed based on that. The weight of the workpiece is CBN coating+steel hub, so to know the actual weight of the steel hub an estimation was performed from the study (Murray et al., 2012). The GW of this study had a weight of 0.24 kg, and a coating of 0.0065 kg. From here, the coating value was obtained for the 0.13 kg FLASH GW, and then to obtain the weight of the steel hub, the coating value was subtracted from the total weight, obtaining a final weight of 0.126 for the steel hub.	Lubricant/Coolant	m3	0.096	A mineral oil based emulsion with a concentration of 8 % was used as cutting fluid. The emulsion had a kinematic viscosity of $v_{40}^{\circ C} = 1.2 \text{ mm}^2/\text{s}$. A total volume of 1,200 litres of cutting fluid was stored in the cutting fluid filter. It was assumed that lost cutting fluid is replaced continuously. [1]
	Iron scrap	kg	0.1387798	Source: Ecoinvent	Hexagonal Boron Nitride (HBN) grains	kg	0.0016	For production of CBN/diamond coating 46,7% wt% of CBN [1]	CBN	kg	0.00351	Weight of CBN to make one CBN Grinding Wheel Source (estimation): [2] Murray, V. R., Zhao, F., & Sutherland, J. W. (2012). Life cycle analysis of grinding: a case study of non-cylindrical computer numerical control grinding via a unit-process life cycle inventory approach. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 226(10), 1604–1611. https://doi.org/10.1177/0954405412454102	Water	m3	1.104	Volume of water necessary for the machining of 1 workpiece with a CBN grinding wheel. [1]
	Argon (liquid)	kg	1.1607034	For steel production 9,2 kg/kg steel Source: Ecoinvent	Bond (glass, resin, metallic or electroplate d)	kg	0.00046	For production of CBN/diamond coating 13,2% wt% of CBN [1]	Ni	kg	0.0110	Weight of Nickel to make one CBN Grinding Wheel Source (estimation): [3] A. Moing, Jean-Gabriel Legoux, A. Vardelle, & Themelis, N. J. (2009). LCA Comparison of Electroplating and Other Thermal Spray Processes.				



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												https://doi.org/10.1361/cp2009itsc1207				
	Hexagonal Boron Nitride (HBN)	kg	0.001299	For production of HBN grains 79,2% wt% of HBN grains Source: Winter et al. (2015)	Pore builder	kg	0.0000035	For production of CBN/diamond coating <0,1% wt% of CBN [1]	Epoxy resin	kg	0.00292	[2]				
	Catalyst	kg	0.0003903	For production of HBN grains "LiBaBN2 or LiCaBN2" 23,8% wt% of HBN grains Source: Winter et al. (2015)	Additives	kg	0.0014	For production of CBN/diamond coating 40,1% wt% of CBN "Al2O3, Dextrin and Urea formaldehyde resin" [1]	Water (deionized, normal)	m3	1.257E-04	[3]				
	Calcium oxide	kg	6.954E-06	For production of the bond 1,5% wt% of Bond Source: Winter et al. (2015)					Sulfuric acid	kg	1.445E-04					
	Sodium oxide	kg	2.318E-05	For production of the bond 5,0% wt% of Bond Source: Winter et al. (2015)					Sodium cabonate	kg	7.854E-06					
	Aluminium oxide	kg	8.529E-05	To be completed by 3drivers For production of the bond 5,2% wt% of Bond Source: Winter et al. (2015)					Sodium gluconate	kg	1.885E-05					
	Magnesium oxide	kg	4.636E-07	For production of the bond 0,1% wt% of Bond Source: Winter et al. (2015)	Electricity (cutting)	kWh	1.28	Energy demand: 36.5 MJ/kg [4] Catalano, A. R., Debernardi, L., Balaso, R., Rubbiani, F., Priarone, P. C., & Settineri, L. (2022). An appraisal of the cradle-to-gate energy demand and carbon footprint of high-speed steel cutting tools. Procedia CIRP, 105, 745–750. https://doi.org/10.1016/j.procir.2022.02.124	Trisodium phosphate	kg	1.571E-05					



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	Silicon dioxide	kg	0.000306	For production of the bond 66,0% wt% of Bond Source: Winter et al. (2015)	Electricity (sintering CBN)	kWh	1.83	0,52 kW/gram CBN For sintering of CBN [1]	Caustic soda	kg	3.927 E-05					
	Boron trioxide	kg	0.0001034	For production of the bond 22,3% wt% of Bond Source: Winter et al. (2015)	Heat (cold/hot curing CBN)	MW	0.055	15.52 kWh/kg of CBN For cold/hot curing of CBN [1]								
Inputs from technological sphere (energy)	Electricity (HBN sintering)	kWh	0.0002132	For HBN sintering 0,13 kWh/g HBN grains Source: Winter et al. (2015)	Steel scrap	kg	1.94	100 % recycling was assumed for the aluminium and steel hub. The steel or aluminium hub scrap is transported to the recycler and is recycled into a secondary scrap. This scrap is then sent back as input for the ingot production. The distribution and disposal transportation was assumed as 100 km for the ease of assessment.	Electricity (coating)	kWh	0.278	[4] Fernando, W. L. R., Karunathilake, H. P., & Gamage, J. R. (2021). Strategies to reduce energy and metalworking fluid consumption for the sustainability of turning operation: A review. Cleaner Engineering and Technology, 3, 100100. https://doi.org/10.1016/j.clet.2021.100100	Electricity (grinding)	kWh	0.96	
	Hot rolling (steel)	kg	2.07	For steel production (hot rolling of unalloyed steel) Source: Ecoinvent					Electricity (electroplating)	kWh	0.054	[3]				
	Electricity (steel)	kWh	0.06	For steel production 0,46 kWh/kg steel Source: Ecoinvent					Electricity (sintering)	kWh	0.233	[5] Kruzhanov, V., & Arnhold, V. (2012). Energy consumption in powder metallurgical manufacturing. Powder Metallurgy, 55(1), 14–21. https://doi.org/10.1179/174329012x13318077875722				
Outputs	Carbon Dioxide (fossil)	kg	0.0063082	For steel production 0,05 kg/kg steel Source: Ecoinvent					Chemicals	kg	3.547 E-05					
	Wastewater	m3	1.514E-05	For steel production 0,00012 m3/kg steel Source: Ecoinvent					Wastewater	L	1.257 E-04					
	Nitrogen Oxides	kg	1.262E-05	For steel production												



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				0,0001 kg/kg steel												
				Source: Ecoinvent												

Table 10. Life cycle inventory for the grinding wheel use case: laser scenario.

Life cycle stage	1. Raw materials extraction				2. Production				3. Grinding wheel manufacturing				4. Use phase			
	Parameter	Unit	Source	Observations	Parameter	Unit	Value	Sources	Parameter	Unit	Value	Source	Parameter	Unit	Value	Source
Inputs from technological sphere (materials, water, fuels)	Aluminium ingot	kg	0.2371872	For steel production 1,88 kg/kg steel Source: Ecoinvent	Steel (low-alloyed, hot rolled)	kg	2.067	For steel hub This value was estimated from [1] Winter, M., Ibbotson, S., Kara, S., & Herrmann, C. (2015). Life cycle assessment of cubic boron nitride grinding wheels. Journal of Cleaner Production, 107, 707–721. https://doi.org/10.1016/j.jclepro.2015.05.088 . The study stated that to produce one steel hub of 1 kg, 17 kg of steel were necessary.	Steel hub	kg	0.126	Weight of steel hub to make one CBN Grinding Wheel The total weight of the workpiece (coating+steel hub) was estimated to be 0.13 kg. The dimensions of the GW are 100mm x 10 mm. A standard commercial GW with dimensions of 203.2mm x 38.1 mm has a weight of 2.04 kg. The volume of each workpiece was calculated, and an estimation was performed based on that. The weight of the workpiece is CBN coating+steel hub, so to know the actual weight of the steel hub an estimation was performed from the study (Murray et al., 2012). The GW of this study had a weight of 0.24 kg, and a coating of 0.0065 kg. From here, the coating value was obtained for the 0.13 kg FLASH GW, and then to obtain the weight of the steel hub, the coating value was subtracted from the total weight, obtaining a final weight of 0.126 for the steel hub.	Lubricant/Coolant	m3	0.096	A mineral oil based emulsion with a concentration of 8 % was used as cutting fluid. The emulsion had a kinematic viscosity of $\nu_{40} = 1.2 \text{ mm}^2/\text{s}$. A total volume of 1,200 litres of cutting fluid was stored in the cutting fluid filter. It was assumed that lost cutting fluid is replaced continuously. [1]
	Iron scrap	kg	0.1387798	Source: Ecoinvent	Hexagonal Boron Nitride (HBN) grains	kg	0.0016	For production of CBN/diamond coating 46,7% wt% of CBN [1]	CBN	kg	0.00351	Weight of CBN to make one CBN Grinding Wheel Source (estimation): [2]	Water	m3	1.104	Volume of water necessary for the machining of 1 workpiece with a CBN grinding wheel. [1]
	Argon (liquid)	kg	1.1607034	For steel production 9,2 kg/kg steel Source: Ecoinvent	Bond (glass, resin, metallic or electroplate d)	kg	0.00046	For production of CBN/diamond coating 13,2% wt% of CBN [1]	Argon	L/min	4.92	Source: Partners				



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	Hexagonal Boron Nitride (HBN)	kg	0.001299	For production of HBN grains 79,2% wt% of HBN grains Source: Winter et al. (2015)	Pore builder	kg	0.0000035	For production of CBN/diamond coating <0,1% wt% of CBN [1]	Water (jet, profiling)	m3	0.002	Volume of water for jet guided process Source: [6] https://www.synova.ch/technology/synova-laser-microjet.html#nozzles				
	Catalyst	kg	0.0003903	For production of HBN grains "LiBaBN2 or LiCaBN2" 23,8% wt% of HBN grains Source: Winter et al. (2015)	Additives	kg	0.0014	For production of CBN/diamond coating 40,1% wt% of CBN "Al2O3, Dextrin and Urea formaldehyde resin" [1]	Water (jet, ablation)	m3						
	Calcium oxide	kg	6.954E-06	For production of the bond 1,5% wt% of Bond Source: Winter et al. (2015)												
	Sodium oxide	kg	2.318E-05	For production of the bond 5,0% wt% of Bond Source: Winter et al. (2015)												
	Aluminium oxide	kg	8.529E-05	To be completed by 3drivers For production of the bond 5,2% wt% of Bond Source: Winter et al. (2015)												
	Magnesium oxide	kg	4.636E-07	For production of the bond 0,1% wt% of Bond Source: Winter et al. (2015)	Electricity (cutting)	kWh	1.28	[4]								
	Silicon dioxide	kg	0.000306	For production of the bond 66,0% wt% of Bond Source: Winter et al. (2015)	Electricity (sintering CBN)	kWh	1.83	0,52 kW/gram CBN For sintering of CBN [1]								



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	Boron trioxide	kg	0.0001034	For production of the bond 22,3% wt% of Bond Source: Winter et al. (2015)	Heat (cold/hot curing CBN)	MW	0.055	15.52 kWh/kg of CBN For cold/hot curing of CBN [1]								
Inputs from technological sphere (energy)	Electricity (HBN sintering)	kWh	0.0002132	For HBN sintering 0,13 kWh/g HBN grains Source: Winter et al. (2015)	Steel scrap	kg	1.94	100 % recycling was assumed for the aluminium and steel hub. The steel or aluminium hub scrap is transported to the recycler and is recycled into a secondary scrap. This scrap is then sent back as input for the ingot production. The distribution and disposal transportation was assumed as 100 km for the ease of assessment.	Electricity (laser machining)	kWh	0.1900	Source: [7] Guarino, S., Ponticelli, G. S., & Venettacci, S. (2020). Environmental assessment of Selective Laser Melting compared with Laser Cutting of 316L stainless steel: A case study for flat washers' production. CIRP Journal of Manufacturing Science and Technology, 31, 525–538. https://doi.org/10.1016/j.cirpj.2020.08.004 0.63 MJ/kg for the cutting of the stainless steel sheets at the requested dimensions.	Electricity (grinding)	kWh	0.96	
	Hot rolling (steel)	kg	2.07	For steel production (hot rolling of unalloyed steel) Source: Ecoinvent					Electricity (laser profiling)	kWh						
	Electricity (steel)	kWh	0.06	For steel production 0,46 kWh/kg steel Source: Ecoinvent					Electricity (sintering)	kWh	0.233	[12]				
									Electricity (water jet profiling)	kWh	0.02	Estimated from: [8] https://doi.org/10.3390/ma17143458 (this laser has a laser power output of 1kW). Here it was assumed that the process takes 1 min as the cutting speed is 15 mm/min and the wheel has a width of 10 mm				
									Electricity (water jet ablation)	kWh						
Outputs	Carbon Dioxide (fossil)	kg	0.0063082	For steel production 0,05 kg/kg steel Source: Ecoinvent												
	Wastewater	m3	1.514E-05	For steel production 0,00012 m3/kg steel Source: Ecoinvent												



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	Nitrogen Oxides	kg	1.262E-05	For steel production 0,0001 kg/kg steel Source: Ecoinvent											
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- [8] <https://doi.org/10.3390/ma17143458>



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Table 11. Life cycle inventory for the microdrill use case: conventional scenario.

Life cycle stage	1. Raw materials extraction				2. Production shanks				3. Production micro-drills				4. Use phase			
Inputs from technological sphere (materials, water, fuels)	Parameter	Unit	Value	Observations	Parameter	Unit	Value	Observations	Parameter	Unit	Value	Observations	Parameter	Unit	Value	Observations
	Tungsten concentrate	g	19.1	For obtaining Ammonium Paratungstate 2,12 g/g WC Source: Ecoinvent	Ammonium Paratungstate	g	11.763	For WC production 1,307 g/g WC Source: Ecoinvent	Tungsten carbide shank (WC)	g	9	Weight of component required to produce 1 WC-PCD drill	Lubricant	L	0.096	
					Carbon Black	g	0.63	For WC production 0,07 g/g Tungsten carbide Source: Ecoinvent	Diamonds	g	0.86	Weight of material used for coating of 1 WC-PCD drill	Water	L	1.104	
					Hydrogen	g	0.441	0,049 g/g Tungsten carbide Source: Ecoinvent								
					Graphite	g	1.72	2 g/g diamond Source: [1] Winter, M., Ibbotson, S., Kara, S., & Herrmann, C. (2015). Life cycle assessment of cubic boron nitride grinding wheels. Journal of Cleaner Production, 107, 707–721. https://doi.org/10.1016/j.jclepro.2015.05.088 .								
					Metal solvent (Nickel)	g	1.72	2 g/g diamond [1]								
					WC-Co	g	16.34	Anvils for graphite pressing 19 g/g of diamond Source: [2] Furberg, A., Fransson, K., Mats Zackrisson, Larsson, M., & Rickard Arvidsson. (2020). Environmental and resource aspects of substituting cemented carbide with polycrystalline diamond: The case of machining tools. Journal of Cleaner Production, 277, 123577–123577. https://doi.org/10.1016/j.jclepro.2020.123577								
					Sulfuric acid (recycled)	g	0.2494	0,29 g/g diamond [1]								
					Potassium dichromate (recycled)	g	0.0344	0,04 g/g diamond [1]								
Inputs from technologic	Electricity (Ammonium)	kWh	12.2	1.36 kWh/kgWC powder	Electricity (WC powder production)	kWh	70.2	For WC powder production 7,8kWh/kg WC powder [2]	Electricity (pre-grinding)	kWh	2.5	Source:[2]	Electricity (drilling of 1 workpiece)	kWh	6.11E-04	Estimation made from: [3] Perçin, M., Aslantas,



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al sphere (energy)	Paratungstate production)			Source: Ecoinvent				Source: Ecoinvent									K., Uzun, I., Kaynak, Y., & Çicek, A. (2016). Micro- drilling of Ti-6Al-4V alloy: The effects of cooling/lubricating. Precision Engineering, 45, 450–462. https://doi.org/10.1016/ j.precisioneng.2016.02.015
	Heat	MJ	594	65,96 MJ/kgWC powder Source: Ecoinvent	Electricity	kWh	0.516	For diamond production 0,6 kWh/kg diamond [1]	Electricity (brazing)								
									Electricity (EDG grinding)								
Outputs	Ammonia	g	2.07	0,23 g/g WC powder Source: Ecoinvent	Ammonia	g	0.846	0,094 g/g WC powder Source: Ecoinvent	Carbide shank scraps	g	6						
	Hazardous waste for underground deposit	g	13.3	1,48 g/g WC powder Source: Ecoinvent	CO2	g	0.117	0,013 g/g WC powder Source: Ecoinvent	PCD powder	g	0.360						
	Inert waste	g	16.2	1,80 g/g WC powder Source: Ecoinvent	Hydrogen	g	0.0297	0,0033 g/g WC powder Source: Ecoinvent									
	Municipal solid waste	g	0.45	0,05 g/g WC powder Source: Ecoinvent	WC-Co	g	16.34	Anvils for graphite pressing 19 g/g of diamond									
	Wastewater from ammonium paratungstate production	g	1.98	0,22 g/g WC powder Source: Ecoinvent	Wastewater sulfuric acid + potassium dichromate)	cm3	0.2838	cm3/g synthetic diamond grit. Note that 0.29 g sulfuric acid and 0.040 g potassium dichromate equals 0.17 cm3									
					Nickel metal solvent, recycled	g	1.72	The nickel metal solvent was assumed to be recycled completely since industrial waste nickel catalysts can in general be recovered to a high degree, approaching a 100% recovery rate for many methods. The lowest recovery rate reported by for waste nickel catalysts was 85% and was applied in the sensitivity analysis.									



Table 12. Life cycle inventory for the microdrill use case: laser scenario.

Life cycle stage	1. Raw materials extraction				2. Production shanks				3. Production micro-drills				4. Use phase			
	Parameter	Unit	Value	Observations	Parameter	Unit	Value	Observations	Parameter	Unit	Value	Observations	Parameter	Unit	Value	Observations
Inputs from technological sphere (materials, water, fuels)	Tungsten concentrate	g	15.264	For obtaining Ammonium Paratungstate 2,12 g/g WC Source: Ecoinvent	Ammonium Paratungstate	g	9.4104	For WC production 1,307 g/g WC Source: Ecoinvent	Tungsten carbide shank (WC)	g	7.2	Weight of component required to produce 1 WC-PCD drill [2]	Lubricant	L	0.096	
					Carbon Black	g	0.504	For WC production 0,07 g/g Tungsten carbide Source: Ecoinvent	Diamonds	g	0.86	Weight of material used for coating of 1 WC-PCD drill [2]	Water	L	1.104	
					Hydrogen	g	0.3528	0,049 g/g Tungsten carbide Source: Ecoinvent	gas	L/min	4.92	For production of 1 WC-PCD drill Source: PARTNERS				
					Graphite	g	1.72	2 g/g diamond [1]	Water	L	2	Volume required for the production of 1 drill Source: [4] https://www.synova.ch/technology/synova-laser-microjet.html#nozzles				
					Metal solvent (Nickel)	g	1.72	2 g/g diamond [1]								
					WC-Co	g	16.34	To be completed by 3drivers Anvils for graphite pressing 19 g/g of diamond Source: [1]								
					Sulfuric acid (recycled)	g	0.2494	To be completed by 3drivers 0,29 g/g diamond Source: [1]								
					Potassium dichromate (recycled)	g	0.0344	To be completed by 3drivers 0,04 g/g diamond Source: [1]								
Inputs from technological sphere (energy)	Electricity (Ammonium Paratungstate production)	kWh	9.792	1.36 kWh/kgWC powder Source: Ecoinvent					Electricity (cutting)	kWh	0.001	Source: [5] Guarino, S., Ponticelli, G. S., & Venettacci, S. (2020). Environmental assessment of Selective Laser Melting compared with Laser Cutting of 316L	Electricity (drilling)	kWh	6.11E-04	[3]



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												stainless steel: A case study for flat washers' production. CIRP Journal of Manufacturing Science and Technology, 31, 525–538. https://doi.org/10.1016/j.cirpj.2020.08.004				
	Heat	MJ	474.912	65,96 MJ/kg WC powder Source: Ecoinvent	Electricity (WC powder production)	kWh	0.0562	For WC powder production 7,8kWh/kg WC powder Source: Ecoinvent	Electricity (macro-machining)	kWh						
					Electricity	kWh	0.0005	For diamond production 0,6 kWh/kg diamond [2]	Electricity (micro-machining)	kWh	1.13 542 E-05	PARTNERS: LASER POWER: 65.4 W (Cutting speed: 8mm/sec).				
Outputs	Ammonia	g	1.656	1,80 g/g WC powder Source: Ecoinvent	Ammonia	g	0.68	0,094 g/g WC powder Source: Ecoinvent	Carbide shanks scrap	g	4.20					
	Hazardous waste for underground deposit	g	10.656	0,05 g/g WC powder Source: Ecoinvent	CO2	g	0.09	0,013 g/g WC powder Source: Ecoinvent	PCD powder	g	0.36					
	Inert waste	g	12.96	0,22 g/g WC powder Source: Ecoinvent	Hydrogen	g	0.024	0,0033 g/g WC powder Source: Ecoinvent								
	Municipal solid waste	g	0.36	To be completed by 3drivers 0,05 g/g WC powder Source: Ecoinvent	WC-Co	g	16.34	Anvils for graphite pressing 19 g/g of diamond [2]								
	Wastewater from ammonium paratungstate production	L	1.584	To be completed by 3drivers 0,22 g/g WC powder Source: Ecoinvent	Wastewater sulfuric acid + potassium dichromate)	kg	0.28									
					Nickel metal solvent, recycled	g	1.72									



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Table 13. Life cycle inventory for the cross-car beam use case: conventional scenario.

Life cycle stage	1. Raw materials extraction				2. Production shanks				3. Production micro-drills				4. Use phase			
	Parameter	Unit	Value	Observations	Parameter	Unit	Value	Observations	Parameter	Unit	Value	Observations	Parameter	Unit	Value	Observations
Inputs from technological sphere (materials, water, fuels)	Iron scrap	kg	10.1	To be completed by 3drivers For steel production 1,10 kg/kg steel Source: Ecoinvent	Steel (low-alloyed, hot rolled)	kg	9.22	Weight of material required to produce 1 cross-car beam. Final weight: 8.17kg	Compressed air	Nm3	0.736					
	Aluminium ingot	kg	17.3	To be completed by 3drivers For steel production 1,88 kg/kg steel Source: Ecoinvent	Lubricants (Phosphate-based coating)	kg	0.01	A phosphate-based coating is used, with an approximate usage of between 0.5 and 2 kg per tonne of steel.	Wire consumption	kg	0.114	Source: [1] Xu, J., Liu, J., Lei, W., Lu, Z., & Ying, L. (2025). Research on the Whole Life Cycle Assessment of Automobile Instrument Cross Beam Based on Lightweight. Advances in Environmental and Engineering Research, 06(01), 1–20. https://doi.org/10.21926/aer.2501005				
	Argon (liquid)	kg	84.8	To be completed by 3drivers For steel production 9,2 kg/kg steel Source: Ecoinvent					Iron frame	kg	11.4	[1]				
Inputs from technological sphere (energy)	Electricity (steel)	kWh	4.2	For steel production 0,46 kWh/kg steel Source: Ecoinvent	Electricity (for cutting)	kWh	0.45	Source: Ecoinvent	Electricity (for cleaning)	kWh	0.10	Welding length: 3654 mm Source: TOFAS	Electricity	kWh /100 km	0.068	For EV charging Amount of energy used throughout vehicle useful life Weight vehicle: 1760 kg; 14.7 kWh/100km
									Electricity (for welding)	kWh						
Outputs	Carbon Dioxide (fossil)	kg	0.461	For steel production 0,05 kg/kg steel	Steel	kg	1.05		Electricity (for final assembly)	kWh	3.81	[1]				



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				Source: Ecoinvent												
	Wastewater	m3	0.001	For steel production 0,00012 m3/kg steel Source: Ecoinvent												
	Nitrogen Oxides	kg	9E-04	For steel production 0,0001 kg/kg steel Source: Ecoinvent												

Table 14. Life cycle inventory for the cross-car beam use case: laser scenario.

Life cycle stage	1. Raw materials extraction				2. Production shanks				3. Production micro-drills				4. Use phase			
	Parameter	Unit	Value	Observations	Parameter	Unit	Value	Observations	Parameter	Unit	Value	Observations	Parameter	Unit	Value	Observations
Inputs from technological sphere (materials, water, fuels)	Iron scrap	kg	5.0037	For steel production 1,10 kg/kg steel Source: Ecoinvent	Aluminium wrought alloy	kg	3.17	Weight of material required to produce 1 cross-car beam. From the aluminium and steel density, we estimated how much aluminium would be for the amount of steel. The final weight of the beam is 6.67 kg (1.5 kg less than conventional).	Water	m3	0.0017	Ecoinvent				
	Aluminium ingot	kg	8.5517	For steel production 1,88 kg/kg steel Source: Ecoinvent	Steel	kg	4.55	The remaining was considered to be steel, taking into account that there is a reduction in 1.5 kg from the conventional scenario to the laser scenario	Argon	L/min	4.92	Partners				
	Argon (liquid)	kg	41.849	For steel production 9,2 kg/kg steel Source: Ecoinvent												
	Aluminium, primary, liquid	kg	3.1712	For aluminium production 1 kg/kg Al Source: Ecoinvent												



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	Hot rolling (steel)	kg		For steel production (hot rolling of unalloyed steel) Source: Ecoinvent	Electricity (for laser cutting)	kWh	0.554962	Source: [2] Guarino, S., Ponticelli, G. S., & Venettacci, S. (2020). Environmental assessment of Selective Laser Melting compared with Laser Cutting of 316L stainless steel: A case study for flat washers' production. CIRP Journal of Manufacturing Science and Technology, 31, 525–538. https://doi.org/10.1016/j.cirpj.2020.08.004 0.63 MJ/kg for the cutting of the stainless steel sheets at the requested dimensions.								
	Electricity (steel)	kWh	2.0924	For steel production 0,46 kWh/kg steel Source: Ecoinvent												
Inputs from technological sphere (energy)	Electricity (Al production)	kWh	0.1678	0,0529 kWh/kg Al wrought alloy Source: Ecoinvent					Electricity (for laser cleaning)	kWh	1.71	Assumed that the laser power for welding is 500W. Selected dataset from ecoinvent states that for 1hour of operation 20.5 kWh are consumed. TOFAS states that the laser welding time is 300s. Sources: ecoinvent & partners Laser machining, metal, with YAG-laser, 500W power {RER} laser machining, metal, with YAG-laser, 500W power APOS, S	Electricity 2 km increase	kWh /100 km	0.0547	The electricity calculated here is only relative to the weight of the cross car beam and not to the whole vehicle. Whole vehicle: 14.41 kWh/100 km
	Heat (Al production)	MJ	2.8287	0,892 MJ/kg Al wrought alloy Source: Ecoinvent					Electricity (for final assembly)	kWh	0.132	[1]	Electricity 0.1 km increase	kWh /100 km	0.056	The electricity calculated here is only relative to the weight of the cross car beam and not to the whole vehicle. Whole vehicle: 14.69 kWh/100 km
Outputs	Carbon Dioxide (fossil)	kg	0.2274	For steel production 0,05 kg/kg steel Source: Ecoinvent	Steel	kg	0.62									
	Wastewater	m3	0.0005	For steel production 0,00012 m3/kg steel Source: Ecoinvent	Aluminium	kg	0.43									



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	Nitrogen Oxides	kg	0.0005	For steel production 0,0001 kg/kg steel Source: Ecoinvent												
	Water vapour	m3	0.0005	From Al production 0,00012 m3/kg steel Source: Ecoinvent												
	Suspended solids	kg	0.0004	From Al production 0,00012 m3/kg Al Source: Ecoinvent												
	Dross	kg	0.0444	From Al production 0,014 kg/kg Al Source: Ecoinvent												
	Filter dust	kg	0.0018	From Al production 0,00056 kg/kg Al Source: Ecoinvent												
	Inert waste	kg	0.0057	From Al production 0,0018 kg/kg Al Source: Ecoinvent												
	Wastewater	m3	0.006	From Al production 0,0019 m3/kg Al Source: Ecoinvent												



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References

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- [2] Guarino, S., Ponticelli, G. S., & Venettacci, S. (2020). Environmental assessment of Selective Laser Melting compared with Laser Cutting of 316L stainless steel: A case study for flat washers' production. *CIRP Journal of Manufacturing Science and Technology*, 31, 525–538. <https://doi.org/10.1016/j.cirpj.2020.08.004>



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Table 15. Life cycle inventory for the copper hairpins use case: conventional scenario.

Life cycle stage	2. Production copper hairpins			
Inputs from technological sphere (materials, water, fuels)	Parameter	Unit	Value	Observations
	Copper hairpins	kg	10.63	Source: [1] https://www.researchgate.net/figure/Typical-material-compositions-of-EV-80-KW-PM-motor_fig1_392325833
	Tap water	kg	27.83	Ecoinvent (yag laser process 200W) Please add one line for each kind of consumable. Also, please specify the material
	Metal working machine	kg	0.02	Source: Ecoinvent yag laser process 200W
Inputs from technological sphere (energy)	Electricity (mechanical stripping)	kWh	5.64	Source: [2] Kampker, A., Born, H., Nankemann, M., Hartmann, S., & Franitza, T. (2025). Life Cycle Assessment (LCA) of a Prototypical Hairpin Stator. <i>Lecture Notes in Mechanical Engineering</i> , 108–116. https://doi.org/10.1007/978-3-031-93891-7_13
	Electricity (laser welding)	kWh	0.64	[2]
Outputs	Chips of copper	kg	2.13	Assumption from objectives of FLASH

Table 16. Life cycle inventory for the copper hairpins use case: laser scenario.

Life cycle stage	Production copper hairpins			
Inputs from technological sphere (materials, water, fuels)	Parameter	Unit	Value	Observations
	Copper hairpins	kg	8.5	[1]
	PEEK/PAI coating	kg	7.44E-07	Since no data are available for the PAI coating material, this material is approximate using PE-HD [2]
Inputs from technological sphere (energy)	Electricity (laser stripping)	kWh	2.26	Assumption from objectives of FLASH process
	Electricity (laser welding)	kWh	0.64	Assumption from objectives of FLASH process
Outputs	Chips of copper	kg	0	Assumption from objectives of FLASH process

References:

[1] https://www.researchgate.net/figure/Typical-material-compositions-of-EV-80-KW-PM-motor_fig1_392325833

[2] Kampker, A., Born, H., Nankemann, M., Hartmann, S., & Franitza, T. (2025). Life Cycle Assessment (LCA) of a Prototypical Hairpin Stator. *Lecture Notes in Mechanical Engineering*, 108–116. https://doi.org/10.1007/978-3-031-93891-7_13



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Annex II- Simapro models for use cases

Documentação	Entrada/saída	Parâmetros	Descrição do sistema
Produtos			
Saídas conhecidas para a esfera tecnológica. Produtos e co-produtos		Quantidade	Unidade Grandeza Alocação Tipo de resid Categoria Comentário
Titanium (GLO) market for titanium APOS, S, FLASH hip implant LASER_De25		1	kg Mass 100 % Non-ferro ...Transformation
(Insira linha aqui)			
Saídas conhecidas para a esfera tecnológica. Produtos evitados		Quantidade	Unidade Distribuição SD^2 eller 2' Min Máx
(Insira linha aqui)			
Entradas			
Entradas conhecidas da natureza (recursos)		Sub-compartimento	Quantidade Unidade Distribuição SD^2 eller 2' Min Máx Comentário
(Insira linha aqui)			
Entradas conhecidas da esfera tecnológica (materiais/combustíveis)		Quantidade	Unidade Distribuição SD^2 eller 2' Min Máx Comentário
Helium, crude (GLO) market for APOS, S		0,00484092	kg Indefinido
Tap water (Europe without Switzerland) market for APOS, S		2,909028	kg Indefinido
Argon, liquid (RER) market for argon, liquid APOS, S		2,06944*10^-3+2,10512*10^	kg
Titanium (GLO) titanium production APOS, U, FLASH laser cutting		55,9*10^-3 = 0,0559	kg
(Insira linha aqui)			
Entradas conhecidas da esfera tecnológica (electricidade/calor)		Quantidade	Unidade Distribuição S Comentário
Electricity, medium voltage (GB) market for APOS, S		0,08	kWh Indefinido
Electricity, medium voltage (GB) market for APOS, S		7,73E-04+5,76333E-05 =	kWh
Electricity, medium voltage (GB) market for APOS, S		0,003741667+0,003681667	kWh
Electricity, medium voltage (GB) market for APOS, S		0,000910469+0,000415097	kWh
Electricity, medium voltage (GB) market for APOS, S		9,24*10^-5 = 9,24E-5	kWh
(Insira linha aqui)			
Saídas conhecidas para a esfera tecnológica. Resíduos e emissões para tratamento		Quantidade	Unidade Distribuição SD^2 eller 2' Min Máx Comentário
Inert waste, for final disposal (RoW) treatment of inert waste, inert material landfill APO		0,00603438	kg Indefinido
(Insira linha aqui)			

Figure 14. Model for the acetabular cup use case: laser scenario.



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Produtos									
Saídas conhecidas para a esfera tecnológica. Produtos e co-produtos			Quantidade	Unidade	Grandeza	Alocação	Tipo de resid	Categoria	Comentário
Titanium {GLO} market for titanium APOS, S, FLASH hip implant LASER additive_De25			1	kg	Mass	100 %	Non-ferro	...\Transformation	
(Insira linha aqui)									
Saídas conhecidas para a esfera tecnológica. Produtos evitados			Quantidade	Unidade	Distribuição	SD^2 eller 2' Min	Máx		
(Insira linha aqui)									
Entradas									
Entradas conhecidas da natureza (recursos)		Sub-compartimento	Quantidade	Unidade	Distribuição	SD^2 eller 2' Min	Máx	Comentário	
(Insira linha aqui)									
Entradas conhecidas da esfera tecnológica (materiais/combustíveis)			Quantidade	Unidade	Distribuição	SD^2 eller 2' Min	Máx	Comentário	
Helium, crude {GLO} market for APOS, S			12,23082*10^-3 = 0,0122	kg					
Tap water {Europe without Switzerland} market for APOS, S			2,909028	kg	Indefinido				
Titanium {GLO} titanium production APOS, U, FLASH laser cutting AM			55,9*10^-3 = 0,0559	kg					
Argon, liquid {RER} market for argon, liquid APOS, S			2,06944*10^-3+2,10512*10^-3	kg					
(Insira linha aqui)									
Entradas conhecidas da esfera tecnológica (electricidade/calor)			Quantidade	Unidade	Distribuição	S	Comentário		
Electricity, medium voltage {GB} market for APOS, S			0,08	kWh	Indefinido		water jet cutting anti-rotation		
Electricity, medium voltage {GB} market for APOS, S			7,73E-04+5,76333E-05 = 0,000831	kWh			Hole profile 1 drilling		
Electricity, medium voltage {GB} market for APOS, S			0,003741667+0,003681667+0,00082745 = 0,00825	kWh			Hole profile 2 drilling		
Electricity, medium voltage {GB} market for APOS, S			0,000910469+0,000415097 = 0,00133	kWh			Surfacing area		
Electricity, medium voltage {GB} market for APOS, S			9,24*10^-5 = 9,24E-5	kWh			Surfacing anti-rotation		
(Insira linha aqui)									
Saídas conhecidas para a esfera tecnológica. Resíduos e emissões para tratamento			Quantidade	Unidade	Distribuição	SD^2 eller 2' Min	Máx	Comentário	
Inert waste, for final disposal {RoW} treatment of inert waste, inert material landfill APO			0,00603438	kg	Indefinido				
(Insira linha aqui)									

Figure 15. Model for the acetabular cup use case: AM scenario.



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Produtos									
Saídas conhecidas para a esfera tecnológica. Produtos e co-produtos					Quantidade	Unidade	Grandeza	Alocação	Tipo
Titanium {GLO} market for titanium APOS, S, FLASH hip implant conv_Nov25					1	kg	Mass	100 %	No
(Insira linha aqui)									
Saídas conhecidas para a esfera tecnológica. Produtos evitados					Quantidade	Unidade	Di		
(Insira linha aqui)									
Entradas									
Entradas conhecidas da natureza (recursos)		Sub-compartimento	Quantidade	Unidade	Distribuição	SD^2 eller 2'	Min	Máx	Comentário
Water, cooling, unspecified natural origin, Europe without Austria		in water	0,31	m3	Indefinido				
Air		in air	404	kg	Indefinido				
(Insira linha aqui)									
Entradas conhecidas da esfera tecnológica (materiais/combustíveis)				Quantidade	Unidade	Distribuição	SD^2 eller 2'	N	
Titanium {GLO} titanium production APOS, U, FLASH conv+laser				134,61/1000 = 0,135	kg				
Titanium sponge {GLO} market for titanium sponge APOS, U; FLASH coating				0,001	kg	Indefinido			
Lubricating oil {RER} market for lubricating oil APOS, S				0,34	kg	Indefinido			
Tap water {RER} market group for APOS, S				260	kg	Indefinido			
(Insira linha aqui)									
Entradas conhecidas da esfera tecnológica (electricidade)		Quantidade	Unidade	Distribuição	S	Comentário			
Electricity, medium voltage {GB} market for APOS, S		0,17+0,02	kWh			Mill turning+coating			
Electricity, medium voltage {GB} market for APOS, S		1,91	kWh	Indefinido		Turning			
Electricity, medium voltage {GB} market for APOS, S		0,042	kWh	Indefinido		laser marking			
(Insira linha aqui)									
Saídas conhecidas para a esfera tecnológica. Resíduos e emissões para tratamento			Quantidade	Unidade	D				
Inert waste, for final disposal (RoW) treatment of inert waste, inert material landfill A			78,71*10^-3+0,00603438 = 0,0847	kg					
Waste mineral oil {Europe without Switzerland} market for waste mineral oil APOS, :			0,27	kg	Ir				
(Insira linha aqui)									

Figure 16. Model for the acetabular cup use case: conventional scenario.



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Saídas conhecidas para a esfera tecnológica. Produtos e co-produtos					Quantidade	Unidade	Grandeza	Alocação	Tipo de resíduo	Categoria
FLASH GW conventional					0,13	kg	Massa	100 %	não definido	...
(Insira linha aqui)										
Saídas conhecidas para a esfera tecnológica. Produtos evitados						Quantidade		Unidade	Distribuição	SD^2
(Insira linha aqui)										
Entradas										
Entradas conhecidas da natureza (recursos)					Sub-compartimento	Quantidade	Unidade	Distribuição	SD^2	Min
(Insira linha aqui)										
Entradas conhecidas da esfera tecnológica (materiais/combustíveis)						Quantidade	Unidade	Distribuição	SD^2	Min
Manufacturing of CBN FLASH GW						0,004	kg	Indefinido		
Steel hub FLASH						0,126	kg	Indefinido		
Chemicals & water for electroplating FLASH GW						14	kg	Indefinido		
Epoxy resin, liquid (RER) market for epoxy resin, liquid APOS, S						0,003	kg	Indefinido		
(Insira linha aqui)										
Entradas conhecidas da esfera tecnológica (eletricidade/calor)					Quantidade	Unidade	Distribuição	S	Comentário	
Electricity, high voltage (RER) market group for APOS, S					0,28	kWh	Indefinido		Coating	
Electricity, high voltage (RER) market group for APOS, S					0,054	kWh	Indefinido		Electroplating	
Electricity, high voltage (RER) market group for APOS, S					0,233	kWh	Indefinido		Sintering	
(Insira linha aqui)										

Figure 17. Model for the grinding wheel use case: conventional scenario (production).



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Produtos							
Saídas conhecidas para a esfera tecnol	Quantidade	Unidade	Grandeza	Alocação	Categoria	Comentário	
Use phase GW conv FLASH	1	kg	Mass	100 %	Others		
(Insira linha aqui)							
Saídas conhecidas para a esfera tecnológica. Produtos evitados						Quantidade	
(Insira linha aqui)						Unidade	
Entradas							
Entradas conhecidas da natureza (recursos)	Sub-compartimento	Quantidade	Unidade	Distribuição	SD^2 eller 2* Min	Máx	Comentário
(Insira linha aqui)							
Entradas conhecidas da esfera tecnológica (materiais/combustíveis)		Quantidade	Unidade	Distribuição	SD^2 eller 2 Min	Máx	Comer
Tap water {Europe without Switzerland} market for APOS, S		1104	kg	Indefinido			
Lubricating oil {RER} market for lubricating oil APOS, S		96	kg	Indefinido			
(Insira linha aqui)							
Entradas conhecidas da esfera tecnológica (electricidade/calor)			Quantidade	Unidade			
Electricity, medium voltage {Europe without Switzerland} market group for APOS, S			769,76	kWh			
(Insira linha aqui)							
Saídas							

Figure 18. Model for the grinding wheel use case: conventional scenario (use phase).



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Produtos				
Especificação de resíduos	Quantidade	Unidade	Categoria	Comentário
Recycling_ccb conv	1	kg	Recycling	

Entradas				
Entradas conhecidas da esfera tecnológica (materiais/combustíveis)	Quantidade	Unidade	Distribuição	SD^2 eller 2 Mir
(Insira linha aqui)				
Entradas conhecidas da esfera tecnológica (electricidade/calor)	Quantidade			
(Insira linha aqui)				

Saídas		
Materiais e/ou fracções separadas do fluxo de resíduos	Tipo de Material/Res	Porcentagem
Steel and iron (waste treatment) {GLO} recycling of steel and iron APOS, S	Steel	100 %
(Insira linha aqui)		

Fluxos de resíduos restantes depois da separação	Porcentagem	Cc
Municipal solid waste (waste scenario) {Europe without Switzerland} Treatment of municipal solid waste, landfill APOS, S	100 %	
(Insira linha aqui)		

Figure 19. Model for the grinding wheel use case: conventional scenario (end-of-life).



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Produtos									
Saídas conhecidas para a esfera tecnológica. Produtos e co-produtos				Quantidade	Unidade	Grandeza	Alocação	Tipo de resid	Categoria
FLASH GW LASER				0,13	kg	Mass	100 %	não definido	...\Transfor
(Insira linha aqui)									
Saídas conhecidas para a esfera tecnológica. Produtos evitados					Quantidade	Unidade	Distribuição	SD^2 eller	
(Insira linha aqui)									
Entradas									
Entradas conhecidas da natureza (recursos)		Sub-compartimento	Quantidade	Unidade	Distribuição	SD^2 eller 2'	Min	Máx	Comentário
(Insira linha aqui)									
Entradas conhecidas da esfera tecnológica (materiais/combustíveis)			Quantidade	Unidade	Distribuição	SD^2 eller 2	Min	Máx	
Manufacturing of CBN FLASH GW			0,004	kg	Indefinido				
Steel hub FLASH			0,126	kg	Indefinido				
Argon, liquid {RER} market for argon, liquid APOS, S			$4,92 \cdot 1,78 \cdot 10^{-3} = 0,00876$	kg					
Tap water {Europe without Switzerland} market for APOS, S			$0,002 \cdot 10^3 = 2$	kg					
(Insira linha aqui)									
Entradas conhecidas da esfera tecnológica (electricidade/calor)		Quantidad	Unidade	Distribuição	S	Comentário			
Electricity, high voltage {RER} market group for APOS, S		0,19	kWh	Indefinido		Laser machining + laser profiling			
Electricity, high voltage {RER} market group for APOS, S		0,233	kWh	Indefinido		Sintering			
Electricity, high voltage {RER} market group for APOS, S		0,02	kWh	Indefinido		Water jet			
(Insira linha aqui)									

Figure 20. Model for the grinding wheel use case: laser scenario (production).



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Produtos						
Saídas conhecidas para a esfera tecnol	Quantidad	Unidade	Grandeza	Alocação	Categoria	Comentário
Use phase GW laser FLASH	1	kg	Mass	100 %	Others	
(Insira linha aqui)						
Saídas conhecidas para a esfera tecnológica. Produtos evitados						Quantidade
(Insira linha aqui)						Unidade

Entradas							
Entradas conhecidas da natureza (recursos)	Sub-compartimento	Quantidade	Unidade	Distribuição	SD^2 eller 2' Min	Máx	Comentário
(Insira linha aqui)							
Entradas conhecidas da esfera tecnológica (materiais/combustíveis)		Quantidade	Unidade	Distribuição	SD^2 eller 2 Min	Máx	Comer
Tap water {Europe without Switzerland} market for APOS, S		1104	kg	Indefinido			
Lubricating oil {RER} market for lubricating oil APOS, S		96	kg	Indefinido			
(Insira linha aqui)							
Entradas conhecidas da esfera tecnológica (electricidade/calor)			Quantidade	Unidade			
Electricity, medium voltage {Europe without Switzerland} market group for APOS, S			923,71	kWh			
(Insira linha aqui)							

Figure 21. Model for the grinding wheel use case: laser scenario (use phase).



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Produtos										
Saídas conhecidas para a esfera tecnol	Quantidad	Unidade	Grandeza	Alocação	Tipo de resid	Categoria	Comentário			
FLASH Microdrill_conventional	3,5	g	Mass	100 %	não definidc	...\Transformation				
(Insira linha aqui)										
Saídas conhecidas para a esfera tecnológica. Produtos evitados						Quantidade	Unidade	Distribuição	SD^2 eller 2'	
(Insira linha aqui)										
Entradas										
Entradas conhecidas da natureza (recursos)			Sub-compartimento	Quantidade	Unidade	Distribuição	SD^2 eller 2'	Min	Máx	Comentário
(Insira linha aqui)										
Entradas conhecidas da esfera tecnológica (materiais/combustíveis)				Quantida	Unidade	Distribuição	SD^2 eller 2	Min	Máx	Comentário
Tungsten carbide powder {GLO} market for tungsten carbide powder APOS, S				9	g	Indefinido				
FLASH PCD manufacturing				0,86	g	Indefinido				
(Insira linha aqui)										
Entradas conhecidas da esfera tecnológica (electricidade/calor)						Quantidade	Unidade	Distribuição	S	Co
Electricity, high voltage {RER} market group for APOS, S						2,5	kWh	Indefinido		
(Insira linha aqui)										

Figure 22. Model for the microdrill use case: conventional scenario (production).



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Saídas conhecidas para a esfera tecnol	Quantidade	Unidade	Grandeza	Alocação	Categoria	Comentário
Use phase microdrill conv FLASH	1	kg	Mass	100 %	Others	
(Insira linha aqui)						
Saídas conhecidas para a esfera tecnológica. Produtos evitados						Quantidade
(Insira linha aqui)						Unidade
						Distribuição
						SD^2 eller 2'
Entradas						
Entradas conhecidas da natureza (recursos)	Sub-compartimento	Quantidade	Unidade	Distribuição	SD^2 eller 2'	Min
(Insira linha aqui)						Máx
Entradas conhecidas da esfera tecnológica (materiais/combustíveis)		Quantidade	Unidade	Distribuição	SD^2 eller 2'	Min
Tap water {Europe without Switzerland} market for APOS, S		1104	kg	Indefinido		
Lubricating oil {RER} market for lubricating oil APOS, S		96	kg	Indefinido		
(Insira linha aqui)						
Entradas conhecidas da esfera tecnológica (electricidade/calor)		Quantidade			Unidade	Distribuição
Electricity, medium voltage {Europe without Switzerland} market group for APOS, S		110			kWh	Indefinido
(Insira linha aqui)						

Figure 23. Model for the microdrill use case: conventional scenario (use phase).



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Produtos									
Saídas conhecidas para a esfera tecnol		Quantidad	Unidade	Grandeza	Alocação	Tipo de resid	Categoria	Comentário	
FLASH Microdrill_laser		3,5	g	Mass	100 %	não definido	...Transformation		
(Insira linha aqui)									
Saídas conhecidas para a esfera tecnológica. Produtos evitados				Quantidade	Unidade	Distribuição	SD^2 eller 2'	Min	Má
(Insira linha aqui)									
Entradas									
Entradas conhecidas da natureza (recursos)		Sub-compartimento	Quantidade	Unidade	Distribuição	SD^2 eller 2'	Min	Máx	Comentário
(Insira linha aqui)									
Entradas conhecidas da esfera tecnológica (materiais/combustíveis)		Quantidade	Unidade	Distribuição	SD^2 eller 2'	Min	Máx	Comentário	
Tungsten carbide powder {GLO} market for tungsten carbide powder APOS, S		7,2	g	Indefinido					
FLASH PCD manufacturing		0,86	g	Indefinido					
(Insira linha aqui)									
Entradas conhecidas da esfera tecnológica (electricidade/calor)		Quantidade	Unidade	Distribuição	S	Comentário			
Electricity, high voltage {RER} market group for APOS, S		0,001	kWh	Indefinido					
(Insira linha aqui)									

Figure 24. Model for the microdrill use case: laser scenario (production).

Produtos									
Saídas conhecidas para a esfera tecnol		Quantidad	Unidade	Grandeza	Alocação	Categoria	Comentário		
Use phase microdrill laser FLASH		1	kg	Mass	100 %	Others			
(Insira linha aqui)									
Saídas conhecidas para a esfera tecnológica. Produtos evitados				Quantidade	Unidade	Distribuição	SD^2 eller 2'	Min	Má
(Insira linha aqui)									
Entradas									
Entradas conhecidas da natureza (recursos)		Sub-compartimento	Quantidade	Unidade	Distribuição	SD^2 eller 2'	Min	Máx	Comentário
(Insira linha aqui)									
Entradas conhecidas da esfera tecnológica (materiais/combustíveis)		Quantidade	Unidade	Distribuição	SD^2 eller 2'	Min	Máx	Comentário	
Tap water {Europe without Switzerland} market for APOS, S		1104	kg	Indefinido					
Lubricating oil {RER} market for lubricating oil APOS, S		96	kg	Indefinido					
(Insira linha aqui)									
Entradas conhecidas da esfera tecnológica (electricidade/calor)		Quantidade	Unidade	Distribuição	S	Comentário			
Electricity, medium voltage {Europe without Switzerland} market group for APOS, S		132	kWh	Indefinido					
(Insira linha aqui)									

Figure 25. Model for the microdrill use case: laser scenario (use phase).



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Nome		Estado		Comentário	
Cross car beam_conv		Nenhum			
Materiais/Montagens		Quantidade	Unidade	Distribuição	SD^2 eller
FLASH Manufacturing steel CONV		1	kg	Indefinido	
Lubricating oil {RER} market for lubricating oil APOS, S		0,01	kg	Indefinido	
(Insira linha aqui)					
Processos		Quantidade	Unidade	Distribuição	SD^2
Metal working, average for steel product manufacturing {RER} process		9,22	kg	Indefinido	
Compressed air, 600 kPa gauge {RER} market for compressed air, 600 k		0,736	m3	Indefinido	
Welding, arc, steel {RER} processing APOS, S		3,654	m	Indefinido	
Electricity, medium voltage (Europe without Switzerland) market grou		3,81	kWh	Indefinido	
(Insira linha aqui)					

Figure 26. Model for the cross-car beam use case: conventional scenario (production).

Nome			
Cross car beam_conv			
Montagem	Quantidade	Unidade	D
Cross car beam_conv	1	p	lr
Processos		Quantidade	
Electricity, low voltage {Europe without Switzerland} market group for		102,3571023	
(Insira linha aqui)			
Cenário de destino final/resíduos			
CCB_conv eol			
Ciclos de vida adicionais		Número	D
(Insira linha aqui)			

Figure 27. Model for the cross-car beam use case: conventional scenario (use phase).



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Nome	Estado	Comentário				
Cross car beam_laser	Nenhum					

Materiais/Montagens	Quantidade	Unidade	Distribuição	SD^2 eller 2*SD	Min	Máx	C
FLASH Manufacturing Al CCB laser	1	kg	Indefinido				
Lubricating oil {RER} market for lubricating oil APOS, S	0,01	kg	Indefinido				
FLASH Component manufacturing steel CCB laser	1	kg	Indefinido				
Argon, liquid {RER} market for argon, liquid APOS, S	$4,92 \cdot 1,78 \cdot 10^{-3} = 0,00876$	kg					
Tap water {Europe without Switzerland} market for APOS, S	0,0017	kg	Indefinido				
(Insira linha aqui)							

Processos	Quantidade	Unidade	Distribuição	S
Metal working, average for steel product manufacturing {RER} processing APOS, U	4,55	kg	Indefinido	
Electricity, medium voltage {Europe without Switzerland} market group for APOS, S	0,56	kWh	Indefinido	
Electricity, medium voltage {Europe without Switzerland} market group for APOS, S	$1,71 + 3,81 = 5,52$	kWh		
(Insira linha aqui)				

Figure 28. Model for the cross-car beam use case: laser scenario (production).



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Nome			Estado	
Cross car beam_laser_0.1km			Nenhum	
Montagem	Quantidade	Unidade	Distribuição	SD^2
Cross car beam_laser	1	p	Indefinido	
Processos		Quantidade		
Electricity, low voltage (Europe without Switzerland) market group for		83,5522169		
(Insira linha aqui)				
Cenário de destino final/resíduos				
CCB_laser eol				
Ciclos de vida adicionais		Número	Distribuição	SD^2
(Insira linha aqui)				

Figure 29. Model for the cross-car beam use case: laser scenario 0.1 km range increase (use phase).

Nome			Estado		Comentário	
Cross car beam_laser_2km			Nenhum			
Montagem	Quantidade	Unidade	Distribuição	SD^2 eller 2*SD	Min	Má
Cross car beam_laser	1	p	Indefinido			
Processos		Quantidade		Unidade	Distribuição	
Electricity, low voltage (Europe without Switzerland) market group for		81,99585208		kWh	Indefinido	
(Insira linha aqui)						
Cenário de destino final/resíduos						
CCB_laser eol						
Ciclos de vida adicionais		Número	Distribuição	SD^2 eller 2*SD	Min	Má
(Insira linha aqui)						

Figure 30. Model for the cross-car beam use case: laser scenario 2 km range increase (use phase).



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Saídas conhecidas para a esfera tecnológica. Produtos e co-produtos				Quantidade	Unidade	Grandeza	Alocação	Tipo de resid	Categoria	Comentário
FLASH Copper hairpins conv				1	kg	Mass	100 %	não definidc	...\Transformation	
(Insira linha aqui)										
Saídas conhecidas para a esfera tecnológica. Produtos evitados							Quantidade	Unidade	Distribuição	SD^2 eller 2' Min
(Insira linha aqui)										
Entradas										
Entradas conhecidas da natureza (recursos)				Sub-compartimento	Quantidade	Unidade	Distribuição	SD^2 eller 2' Min	Máx	Comentário
(Insira linha aqui)										
Entradas conhecidas da esfera tecnológica (mater		Quantida	Unidade	Distribuição	SD^2 eller 2' Min	Máx	Comentário			
Copper, cathode {GLO} market for APOS, S		10,63	kg	Indefinido						
Metal working machine, unspecified {RER} mark		0,02	kg	Indefinido						
Tap water {RER} market group for APOS, U		27,83	kg	Indefinido						
(Insira linha aqui)										
Entradas conhecidas da esfera tecnológica (electricidade/calor)						Quantidade	Unidade	Distribuição	S	Comentário
Electricity, medium voltage {IT} market for APOS, S						5,64	kWh	Indefinido		Stripping
Electricity, medium voltage {IT} market for APOS, S						0,64	kWh	Indefinido		Joining
(Insira linha aqui)										
Saídas conhecidas para a esfera tecnológica. Resíduos e emissões para tratamento										
Saídas conhecidas para a esfera tecnológica. Resíduos e emissões para tratamento					Quantidade	Unidade	Distribuição	SD^2		
Inert waste, for final disposal {RoW} treatment of inert waste, inert material landfill					2,13	kg	Indefinido			
(Insira linha aqui)										

Figure 31. Model for the copper hairpins use case: conventional scenario.



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Produtos									
Saídas conhecidas para a esfera tecnológica. Produtos e co-produtos				Quantidade	Unidade	Grandeza	Alocação	Tipo de resid	Comentário
FLASH Copper hairpins LASER				1	kg	Mass	100 %	não definid	...\Transformation
(Insira linha aqui)									
Saídas conhecidas para a esfera tecnológica. Produtos evitados				Quantidade	Unidade	Distribuição	SD^2 eller 2' Min	Máx	
(Insira linha aqui)									
Entradas									
Entradas conhecidas da natureza (recursos)		Sub-compartimento	Quantidade	Unidade	Distribuição	SD^2 eller 2' Min	Máx	Comentário	
(Insira linha aqui)									
Entradas conhecidas da esfera tecnológica (mater		Quantida	Unidade	Distribuição	SD^2 eller 2' Min	Máx	Comentário		
Copper, cathode {GLO} market for APOS, S		8,5	kg	Indefinido					
(Insira linha aqui)									
Entradas conhecidas da esfera tecnológica (electricidade/calor)				Quantidade	Unidade	Distribuição	S	Comentário	
Electricity, medium voltage {IT} market for APOS, S				2,26	kWh	Indefinido		Stripping	
Electricity, medium voltage {IT} market for APOS, S				0,26	kWh	Indefinido		Joining	
(Insira linha aqui)									

Figure 32. Model for the copper hairpins use case: laser scenario.