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Integrated methodology for sustainability assessment of several innovative materials and processes in different industrial scenarios

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This dissertation is submitted for the degree of:
Doctor of Philosophy

Burgos, June 2023

“Las cosas podían haber sucedido de cualquier otra manera y, sin embargo, sucedieron así.”

Miguel Delibes, ‘El camino’

Agradecimientos:

En primer lugar, me gustaría agradecer a la Dra. Rocío Barros García y a Sonia Martel Martín por la oportunidad que me ofrecieron para trabajar con ellas y el resto del equipo. Puedo decir sin duda que es la mejor etapa laboral de mi carrera. Su apoyo y su plena confianza en mí, otorgándome siempre libertad para desarrollar el trabajo, ha hecho que el proceso de esta tesis haya sido mucho más llevadero. Gracias porque sois fundamentales en el buen ambiente que se respira cada mañana de trabajo. Gracias también al Dr. Jesús Manuel Alegre Calderón, por su disponibilidad en todo momento, y sobre todo por su experiencia y consejos en todo este tiempo, que han mejorado sin lugar a dudas la calidad de la tesis. Indudable es también la importancia de la Dra. Elorri Igos, por acogerme durante tres meses en mi estancia en el *Luxembourg Institute of Science and Technology*; su orientación ha sido indispensable para la consecución de esta tesis.

He de agradecer la ayuda predoctoral concedida por la Orden EDU/1508/2020 de la Consejería de Educación de la Junta de Castilla y León, cofinanciada por el Fondo Social Europeo, que ha sufragado mi contrato para elaborar esta tesis. También a la Comisión Europea, por financiar el proyecto LightMe (G.A. 814552) enmarcado en el programa Horizonte 2020, y dentro del que se ha desarrollado la presente investigación.

A mis compañeros del ICCRAM, tanto a los que continúan como a los que en algún momento pasaron por allí, por hacer todos los días más amenos, por el continuo aprendizaje y por haber aceptado tan bien a un *pucelano*, especialmente a los que ya os habéis convertido en más que compañeros, amigos, gracias por los buenos momentos vividos tanto dentro como fuera del trabajo. Quería particularmente agradecer a Jesús (que nadie se me ponga celoso) por las innumerables horas tratando todos los temas habidos y por haber, y el tiempo invertido en investigar y hablar acerca de los proyectos, del Análisis de Ciclo de Vida, la Sostenibilidad y otras cosas menos trascendentales, sin duda has sido un pilar importante para conseguir realizar esta tesis.

A mis abuelos, los que aún me cuidan desde aquí y los que lo hacen desde otro lugar, por haberme dado a mi familia, mis tíos y mis primos, que me quieren y se preocupan tanto por mí todos los días. Os quiero.

A mis padres, porque nada de nada sería posible en mi vida sin ellos. Por todo lo que han dejado atrás y han sacrificado para darnos lo mejor a mi hermano y a mí. Por ser el mejor ejemplo de esfuerzo y constancia y por todo su cariño incondicional. Sé que estáis muy orgullosos de mí, y yo también de vosotros. Os quiero mucho. A mi hermano Jaime, por venir para cambiarme la vida a mejor y enseñarme lo que significa cuidar a alguien y quererle por encima de todo.

A todos mis amigos, los de toda la vida y los que han llegado después, los de un lugar u otro, por todos los momentos vividos y las experiencias compartidas, por hacer todo mucho más divertido y por estar siempre que lo he necesitado.

Por último, y precisamente por ello más importante, quería dar las gracias a Irene. Has soportado mi ausencia en determinados momentos y la distancia que nos separa, simplemente para que pudiera cumplir mis objetivos. Me enseñas cada día a cómo hacer frente a la adversidad sin perder esa sonrisa tan bonita que tienes. Ahora empieza una nueva etapa, todo va a ir mucho mejor y será mucho más fácil. Gracias por estar siempre a mi lado. Te amo.

Resumen:

Los materiales compuestos de matrices metálicas han atraído gran atención en los últimos años, principalmente por sus mejoradas características mecánicas, en especial su baja proporción en peso, lo que les confiere una gran importancia en determinadas industrias como la aeroespacial o automovilística, entre otras.

Sin embargo, y en línea con las actuales tendencias en materia de sostenibilidad y circularidad promovidas por la gran mayoría de políticas internacionales, la preocupación en cuanto a su impacto ambiental ha crecido recientemente debido a la falta de datos y a su gran interrelación con la industria manufacturera.

Es por ello que el objetivo de esta tesis doctoral es investigar, mediante la metodología de Análisis de Ciclo de Vida (ACV), las implicaciones medioambientales que tienen el uso de estos materiales en los procesos industriales que los utilizan, aportando nuevos datos que puedan finalmente apoyar la toma de decisiones en el desarrollo y mejora de las tecnologías para lograr un mejor desempeño ambiental.

En primer lugar, como primera toma de contacto con la metodología, se analiza la producción de pomos de puerta, mediante dos diferentes técnicas de fundición, formados por una aleación entre aluminio y partículas de dióxido de titanio, que le confiere capacidad auto-limpiable. En la segunda parte se compara un método convencional y otro más novedoso de producción de polvo metálico de titanio para su uso en técnicas de fabricación aditiva, profundizando aún más en la metodología de ACV y en el uso y modificación de bases de datos. Por último, se analiza la utilización del material previo en la producción de una caja de cambios, mediante el uso de una técnica convencional de fundición y otra más novedosa de fabricación aditiva, conocida como deposición de energía dirigida (*Direct Energy Deposition* o

DED). Este caso se trata de un análisis prospectivo en el que se evalúan diferentes escenarios de desarrollo y mejora de la nueva tecnología, escalando los parámetros actuales para encontrar un óptimo en el que poder compararla fielmente con su tecnología de contrapartida, mucho más madura. Se realiza mediante un enfoque paso a paso bajo un análisis *ex-ante,* aportando como resultado diferentes recomendaciones de ecodiseño para ayuda en la toma de decisiones en la mejora de tecnologías emergentes.

Los análisis producidos, los datos extraídos y el modelo final creado para comparar tecnologías maduras y en desarrollo, pueden ser claves para evaluar y cuantificar los impactos ambientales en entornos industriales innovadores, identificando puntos críticos y optimizando así los procesos.

Abstract:

Metal Matrix Composites have attracted much attention in recent years, mainly due to their improved mechanical characteristics, in particular their low weight ratio, which makes them of great importance in certain industries such as aerospace or automotive, among others.

However, and in line with the current trends in sustainability and circularity promoted by the vast majority of international policies, concern regarding their environmental impact has recently risen due to the lack of data and their strong interrelation with the manufacturing industry.

That is why the aim of this doctoral thesis is to investigate, by means of the Life Cycle Assessment (LCA) methodology, the environmental implications of the use of these materials in the industrial processes, providing with new data that can finally support decision-making in the development and improvement of technologies to achieve better environmental performance.

Firstly, as a first contact with the methodology, the production of doorknobs is analysed, using two different casting techniques, formed by an aluminium alloy and titanium dioxide particles, which gives it a self-cleaning capacity. The second part compares a conventional and a newer method of producing titanium metal powder for its use in additive manufacturing techniques, going further into the LCA methodology and the utilization and modification of databases. Finally, the use of the previous material in the production of a gearbox is analysed, using a conventional casting technique and a newer additive manufacturing technique known as Direct Energy Deposition (DED). This case is a prospective analysis where different scenarios of development and improvement of the new technology are evaluated,

scaling the current parameters to find an optimum at which it can be fairly compared with its much more mature counterpart technology. This is done in a step-by-step approach under an ex-ante analysis, providing as a result different eco-design recommendations to help in the decision making process for the improvement of emerging technologies.

The analyses produced, the data extracted and the final model created to compare mature and developing technologies can be key to assessing and quantifying environmental impacts in innovative industrial backgrounds, identifying critical points and thus optimising processes.

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1. Introduction.

1.1. Background of the industrial need.

The sustainability concept was established by the “Brundtland Report” (World Commission on Environment and Development, 1987) as the possibility to meet the current needs without compromising the necessary resources of the future. More recently, the 2030 Agenda for Sustainable Development, with 17 Sustainable Development Goals (SDGs) and 169 targets, to verify the progress on sustainability, was presented (United Nations, 2015). In 2019, a strategic document by the EU was released to endorse SDGs, underpinning future policies and activities (European Commission, 2019). This regulation has recently driven the trend of research on sustainable industrial processes (Abad-Segura et al., 2020). In addition, since the oil crisis of the 1970s, constant efforts have been made to reduce the weight of transport systems in order to achieve greater energy efficiency (Simionescu et al., 2017). For instance, lighter vehicles consume less fuel (a 10% reduction in vehicle weight can result in a 6%-8% fuel economy improvement (Wenlong et al., 2016)), emit less harmful gases, provide a better performance and easier recyclability, so its development is a top priority (Zhang & Xu, 2022). According to the European Environment Agency (2019) the transport sector represents a 23% of the GHG emissions in Europe, with also a 9.5% accounting for the industrial processes, which makes crucial to advance its development and evolution in a more sustainable way.

In this context, lightweight materials have become increasingly critical for producing components for aircrafts, cars, trains, ships, and defence equipment, especially as lightweight metal and alloys possess high strength-to-weight ratios and low density (Campbell, 2012). Common applications met in the automotive, aerospace, manufacturing, railway and other large niche applications, are of crucial importance for the European Manufacturing Industry providing more than 30,2 million jobs and generating €1999 billion of value (Eurostat, 2019).

The global lightweight materials market size is expected to reach 225.3 billion € by 2024, exhibiting a CAGR of 8.9% during the 2017-2024 forecast period (Grand View Research, 2016). This growth is consequence of the increasing demand for lightweight materials in transport and energy sector industries such as automotive, aerospace and wind energy. In 2015, the automotive segment dominated the overall market in terms of revenue, with an 86% share, as rising awareness about fuel emissions has led manufacturers use lighter components in vehicle design. Moreover, rising material innovation in aviation is expected to improve demand for lightweight materials. Automotive and aerospace sectors represent more than a third of EU's R&D investment, so they have a great importance on the industrial progress (European Commission, 2022). The lightweight metals that will experiment the major growth, leaving aside the high strength steel, are aluminium and titanium (Grand View Research, 2016).

Aluminium is the most produced metal after steel and is manufactured in greater volume than all other non-ferrous metals combined (Brough & Jouhara, 2020). The total world production of primary aluminium was 67 million metric tonnes in 2021, according to data from International Aluminium Institute, (2021). This metal is responsible for about 3% of world's direct industrial CO_2 emissions (IEA, 2021). Titanium, due to its outstanding properties, is becoming the metal of future, playing a significant role in advanced technology (Qiu & Guo, 2022). In 2017, titanium demand was estimated to be more than 8 million tons (Perks & Mudd, 2019). It has a growing importance as it was included in the EU's last list of Critical Raw Materials (European Commission, 2020), therefore production in Europe is critical in view of the demand.

As the demand of lightweight materials is increasing, together with a growing environmental concern pushing for its sustainability (Seetharaman et al., 2022), new engineered solutions are provided, such as the Metal Matrix Composites (MMCs) (Ajay Kumar et al., 2020). These materials are constituent by two or more different ones, normally a metal and a ceramic particle, obtaining several advantages over the regular materials. Some of the characteristics that stand out are: high strength to weight ratio, high fatigue strength, high surface smoothness and appearance, corrosion resistance, improved elevated temperature properties, low thermal expansion coefficient, enhanced electrical performance, wear and abrasion resistance, etc. (Singh et al., 2021). MMCs are spread in aerospace, automobile, transport and infrastructure sectors, using mainly aluminium, titanium and magnesium as a matrix, and SiC, B4C, TiC as ceramic reinforcement particles (Sharma et al., 2020). The global MMCs market size was valued at 339,3 million US dollars in 2019, with an expected compound annual growth rate (CAGR) of 6.4% from 2020 to 2027 (Grand View Research, 2019).

Aluminium Metal Matrix Composites (AMMCs) have a high potential for use in automotive and aerospace applications due to their high corrosion and wear resistance, specific modulus, and weight. They are normally reinforced with borides, carbides and oxides, such as SiC, B4C and TiO2. Casting methods is most simple, suitable, used and cost effective method for its production. (Samal et al., 2020). In the case of Titanium Metal Matrix Composites (TMMCs) they have remarkable mechanical characteristics as low density, high strength, elastic modulus, hardness, corrosion and wear resistance, and a significant weight reduction relative to monolithic alloys, mainly thanks to the use of TiB and TiC as reinforcements (Luo et al., (2019); Hayat et al., (2019); Suresh et al., (2022)). These composites are widely manufactured by Spark Plasma Sintering (SPS) and Additive Manufacturing (AM) processes (Ammisetti & Kruthiventi, 2021).

Today’s processing technologies are not good enough to solve industrial problems in a more efficient and environmentally friendly way. For that reason, the production of high-performance lightweight composite materials should be applied in the development of aerospace, automobile and industrial fields for coming future (Koli et al., 2015).

1.2. LightMe project framework.

This research thesis has been developed under the EU funded “LightMe” project. This project is framed within the Horizon 2020 programme, which was the EU's research and innovation funding programme from 2014-2020, with a budget of nearly 80 billion €. This programme provided grants to research and innovation projects through open and competitive calls for proposals, where legal entities from any country were eligible. The aim was to produce world-class science in Europe, while removing innovation barriers and enabling public and private sectors collaboration in delivering innovation (European Commission, 2011). The programme was divided in three big pillars: (i) “excellent science”, for increasing human and technology talent, through the European Research Council (ERC) or Marie Sklodowska-Curie Actions (MSCA); (ii) “social challenges”, to solve social issues in Europe by health improve, safe food, rural development, biotechnology, fuel alternatives, resource-efficient transport systems and green economy; and (iii) “industrial leadership”, to ensure the competitivity of companies in the industrial and technology field (Kim & Yoo, 2019). LightMe project belongs to this last pillar.

The LightMe project aims to establish an Open Innovation Ecosystem test bed that promote the introduction of new functionalities, features, and capabilities to lightweight metals, assisting technologies in reaching a higher level of maturity. This test bed serves as a point of reference for fostering innovation in the field of lightweight metal matrix nanocomposites (MMnC). The LightMe Ecosystem offer the infrastructure (6 Pilot Lines) and know-how required for efficiently and sustainably scaling up new material concepts linked to lightweight MMnC and advanced materials. The Ecosystem offer services such as monitoring, testing, modelling and simulation, standardization, regulatory compliance, nanosafety, environmental assessment and innovation management in addition to the upscaling units, addressing the industrial needs of SMEs and large businesses that can access the Ecosystem and ensuring the transfer of technology to the market.

To verify the ecosystem's appropriate functioning, 8 different test cases for upscaling and testing are validated. This is done with 6 existing pilot lines, further enhanced and improved so as to be used for upscaling new material concepts and products based on lightweight MMnC. The modifications aim to create composite lightweight metals (Al and Ti alloys reinforced by various types of NPs, such as carbides) with improved characteristics and/or extra functionalities by safely and sustainably incorporating NPs into the production lines. The pilot lines used are the following: Low Pressure Die Casting (LPDC), High Pressure Die Casting (HPDC), Green Sand Casting (GSC), Metal Wire Additive Manufacturing (MWAM) by Laser Metal Deposition (LMD), Powder Additive Manufacturing by Directed Energy Deposition (DED), and Spark Plasma Sintering (SPS) with extrusion.

Using data from pilot lines, the environmental impacts and sustainability of the new materials, products, and process were evaluated and used as the initial point for this research thesis. This is determined by means of the Life Cycle Assessment methodology, using specialized software tool (SimaPro) and guidelines (ISO 14040/14044).

1.3. Scope and objectives.

The aim of this thesis is to contribute to the development and application of quantitative methodologies of Life Cycle Assessment (LCA), for the environmental evaluation of different innovative materials manufacture, and their validation as a tool for decision making in different industrial scenarios.

The industry field is always evolving, so it must adapt to new developing production techniques as well as the creation of innovative materials that satisfy the updated standards for weight reduction, safety enhancement and other mechanical characteristics. At the same time, new European policies and trends, mostly focused on the circular economy, emphasise the significance of minimising the negative effects of these new processes on the environment, resource consumption, waste creation, and cost reduction. In this new context, the use of LCA techniques has been established as quantitative instruments to evaluate globally the effects as well as the crucial areas linked to new procedures for the production of novel materials.

The following specific objectives derived from the aforementioned:

i. Application of LCA as a quantitative tool for the environmental evaluation of manufacturing processes of different metal-based materials.
ii. Identify critical parameters and hotspots, both inputs and outputs in terms of raw materials, energy, water, chemicals, etc., that can act as catalysts for increasing production sustainability.
iii. Create different scenarios for the systems under study, offering optimization strategies.

iv. Systematize and develop an evaluation methodology adapted to the advancement of lightweight materials for the industry sector involved, that allows to obtain predictive results supporting early decision making and better orientation of industrial developments.

1.4. Structure of the document.

This doctoral thesis is based in three different iterative works, aimed for several publications, but with a connected research line between them.

After setting the background, detecting the needs and stablish the scope and objectives in the “Introduction”, chapter two is dedicated to present the basis of the Life Cycle Assessment methodology used in this thesis, which is common for the technical work developed.

The different works are included in chapter three, four, and five. Chapter three, “Life Cycle Assessment for Metal Matrix Composites casting technologies”, compares two different processes to produce a self-cleaning doorknob made up with an AlMg3-TiO2 metal matrix composite. This study served as the foundation for the LCA methodology, setting the bases for a deeper and more complicated analysis developed in the following publications. It has been published in Ecological Indicators. The Chapter four, “Life Cycle Assessment for different metal powder production technologies”, has been influenced by a deeper knowledge in the LCA methodology, being able of create and applied different proxies from databases, thus adapting the study. This work compares the production of Ti6Al4V-TiC MMC powder by HEBM and Ti6Al4V powder by GA. The conclusions and the system build up in this research has also served as basis for the development of the third publication. It is published in Sustainability. In Chapter five, “Ex-ante LCA methodology development: a case study in additive manufacturing gearbox production" a new methodology based on parametric modelling to assess the scaled up of emerging technologies has been developed. This has been proved in an additive manufacturing technique, as it was the most promising within the project. The methodology helps on provide different eco-design recommendations for optimization and improvement on the technique, that support manufacturers on their decision making. At the end of chapters three, four and five there are subchapters that contain supplementary material, which gives additional information about the data used and serves fundamentally to assist the replicability of the assessment by other LCA practitioners.

The “General conclusions and remarks” chapter contains the integrative conclusions to be highlighted as a synthesis of the different works that constitute the present thesis, as well as recommendations to be followed for future work.

2. Life Cycle Assessment background.

Life Cycle Assessment (LCA) is a comparative examination and evaluation of the environmental effects of product systems, based on scientific research. Is centred in a life cycle approach, introducing “cradle-to-gate” and “functional unit” as two key distinctive characteristics to distinguish from other environmental assessment methodologies, making possible to compare product systems with similar purposes (Klöpffer, 2014).

In the late 1960s and early 1970s, when some environmental challenges such as resource and energy efficiency, pollution and waste management gained widespread public attention, partial analysis of product chain systems started to arise. At that time, they were called Resource and Environmental Profile Analysis (REPA) and are now considered as partial and proto LCAs. In the following decades the assessment was conceptualized, but performed distinctively with different methods, approaches, terminologies and results, so a common theoretical framework was needed. During the 90s, related activities around the globe growth remarkably, resulting in production of LCA guides and handbooks, together with the first scientific journals. These lead to a deeper exploration into LCA foundations and its connections with other disciplines. In this period, LCA started to became part of some policies and legislations, so the LCA community collaborated to improve and harmonize the methodology, framework and terminology used. In this century, life cycle thinking has been put into practice and elaboration, increasing life cycle based policies and attention to LCA, leading to two international standards presented in 2006 by the International Organization for Standardization: “ISO 14040:2006. Environmental management - Life cycle assessment - Principles and framework” and “ISO 14044:2006. Environmental management - Life cycle assessment - Requirements and guidelines”. (Guinée et al., 2011).

The development of this international standards was essential to the widespread adoption of LCA by all the global stakeholders, which are widely cited by users and other standardization procedures. They made a big contribution to turning LCA into a serious, reliable, and professional instrument to help decision-making in both public and private companies, rather than being an academic or greenwashing tool (Finkbeiner, 2014).

The LCA methodology used for the development of this research thesis is according to the ISO framework aforementioned (International Organization for Standardization (ISO), 2006a, 2006b) and referring to the recommendations and requirements given by the European ILCD (EC-JRC, 2010) and the last Commission Recommendation on life cycle performance (European Commission, 2021). In addition, the instructions included in “Life Cycle Assessment: Theory and Practice” (Hauschild et al., 2017) were used as a background to complete the study and methodology explanation.

ISO 14040:2006 defines LCA as a technique for assessing the environmental aspects and potential impacts associated with a product or service, by:

- Compiling an inventory of relevant inputs and outputs within an appropriate system boundary.
- Evaluating the potential environmental impacts associated with those inputs and outputs.

– Interpreting the results of the inventory analysis and impact assessment phases with respect to the objectives of the study.

To achieve these purposes, information on inputs and outputs of the entire process needs to be collected and processed. The standardised LCA framework comprehends five phases, as shown in Figure 1:

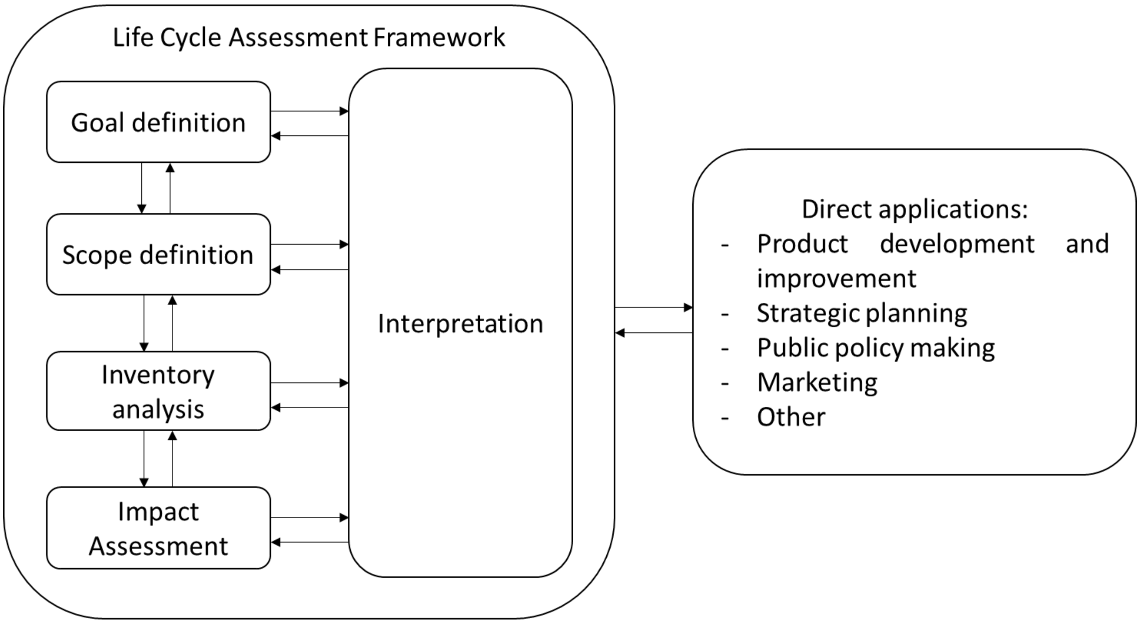

Figure 1. Life Cycle Assessment Framework (ISO 14040:2006).

1. Goal definition: this first phase of the study is where the purpose is established. The goal definition sets the context of the LCA study, and is the basis of the scope definition, where the assessment is framed and outlined in accordance with the goal. The goal must be defined together with the decisions that will be made subject to the results obtained.

   The goal definition based on the ISO standard requirements generally contains six aspects:

   i. Intended applications of the results.
   ii. Limitations due to methodological choices.
   iii. Decision context and reasons for carrying out the study.

   iv. Target audience.
   v. Comparative studies to be disclosed to the public.
   vi. Commissioner of the study and other influential actors.

2. Scope definition: the second phase of the LCA determines what product systems are to be assessed and how this assessment should take place. Together with the goal definition, the scope definition serves as a firm guide for how the subsequent LCA phases should be performed and for how the LCA should be reported. It ensured that the extent, complexity and detail of the study are compatible and consistent to the determined goal. This action implies defining the system, its boundaries (conceptual, geographical and temporal), quality of data, the main hypothesis and the study limitations.

   The main aspects of the scope definition are the following:

   i. Functional unit; which is the unit of the product or service whose environmental impacts will be assessed and/or compared and should be related to the amount of product needed to perform a given function. Questions like “what”, “how much”, “how well”, and “for how long” are answered in order to define and precise the functional unit. The correct definition of the functional unit is essential especially in comparative studies. In case a product delivers less, or lower quality functions compared to a competitor, after the comparison it may appear as better from the environmental point as the same functions (or quality of functions) are not provided by the compared products. This represents an error that has to be avoided in order to preserve the accuracy of the assessment. It is then essential to choose correctly the functional unit considering the same functions for all comparative scenarios. This function is defined by the reference flow, which is the amount and number of products needed to fulfil the lifetime of the studied system.

ii. System boundaries; that delimit the unit processes included into the system. Is based on choices that should be detailed and justified in order to provide confidence in the analysis. The system boundaries should define which stages, process units and flows will be included in the study, following a general supply-chain logic, including all stages from raw material acquisition and pre-processing, production of the main product, product distribution and storage, use stage and end of life treatment of the product. As shown in the Figure 2, many options are available for the selection of the system boundaries, which is strongly dependent on the data availability and their accuracy.

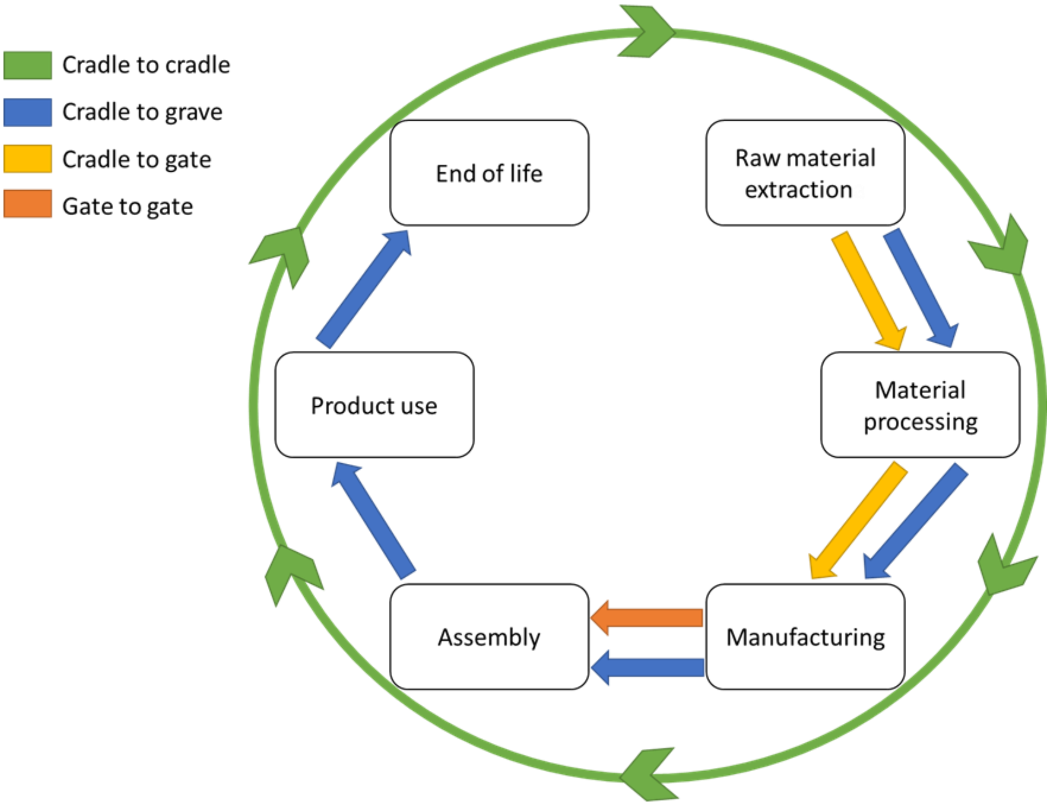

Figure 2. System boundaries. Source: own construction based on ISO 14044:2006.

  - Cradle to cradle is the widest and most complete assessment and it refers to life cycles with potential reuse/recycle loop of the products.
  - Cradle to grave approach expands the boundaries to the disposal of the finished goods.
  - Cradle to gate refers to a life cycle analysis going from the raw materials acquisition to the production of finished goods.
  - Gate to gate refers to life cycles considering only the manufacturing process.

   The goal definition and scope definition are very important to consider when the results of the study are interpreted, since these descriptions involve choices that determine the collection of data and the way the system is modelled and assessed. They therefore have a strong influence on the validity of the conclusions and recommendations that are based on the results of the LCA.

3. <u>Inventory Analysis</u>: this phase, which typically requires the most efforts and resources, is a process of data collection, aiming to quantify, measure and link all the inputs and outputs of the system. In this stage, all emissions released to the environment (air, water, soil and solid waste) and resource consumption (energy and raw materials), along the entire production life cycle, as defined in the scope, and with reference to the functional unit, will be gathered. This flow quantities must be correctly scaled to the assessed product by considering the extent to which the function of each unit process is required to deliver the studied product.

   The main steps are:

   i. data collection;

ii. relevant and non-relevant element identification;
iii. mass and energy balances;
iv. and system burdens allocation.

The inventory analysis requires a structured approach to ensure that time is being spent on collection of data for those parts of the product's life cycle that are most important for the overall impacts from the product system.

Life Cycle Inventory results are the aggregate of elementary flows entering the system and releasing into the environment. The system's product is modelled as unit processes regarding the concept of a black box, where each process is viewed in terms of its inputs and outputs and linked through intermediate product flows. This unit processes represents one or several activities, such as production, transportation, and disposal.

4. Impact Assessment: this stage translates the physical flows and interventions of the product system, applying an impact assessment method, into impacts on the environment. The process identifies and characterizes the potential effects produced in the environment by the system under analysis. For this purpose, a proper software as SimaPro is used, following one or more accepted LCIA methods.

   The impact assessment consists of five elements of which the first three are mandatory according to the ISO 14040 standard:

   i. Selection; of the impact categories representative of the assessment parameters, that can be used to quantify the impact of elementary flows on the representative indicator.

   ii. Classification; of elementary flows from the inventory by assigning them to impact categories according to their ability to contribute by impacting the chosen indicator.
   iii. Characterisation; using environmental models to multiply each of the assigned elementary flows by a factor depending of respectively indicator’s category, to quantify the impact of a product or service, classified in aggregated midpoint impact categories.
   iv. Normalisation; used to express the different impact categories in a common reference value, to compare the magnitude of their contributions.
   v. Weighting; giving each category a quantitative expression of how severe it is relative to the other impact categories, generating endpoint impact categories, to provide a comparable ratio expressed in a single score.

5. <u>Interpretation</u>: in this phase, the results of the study are elucidated in order to answer the questions posed as part of the goal definition. The findings obtained are presented in a synthetic way, showing the critical and main contributors’ sources of impacts and the possible options to reduce them.

   The interpretation requires consistency checks, ensuring that there is complete information. Sensitivity and uncertainty analysis are applied as part of the interpretation to guide the development of conclusions from the results.

All this previously presented steps are clearly ordered, but most of the LCA studies follow an iterative process, which means that procedures are repeated, to refine the results paying major attention to the most relevant processes, resources and emissions. Figure 3 shows how this iterative approach is carried out.

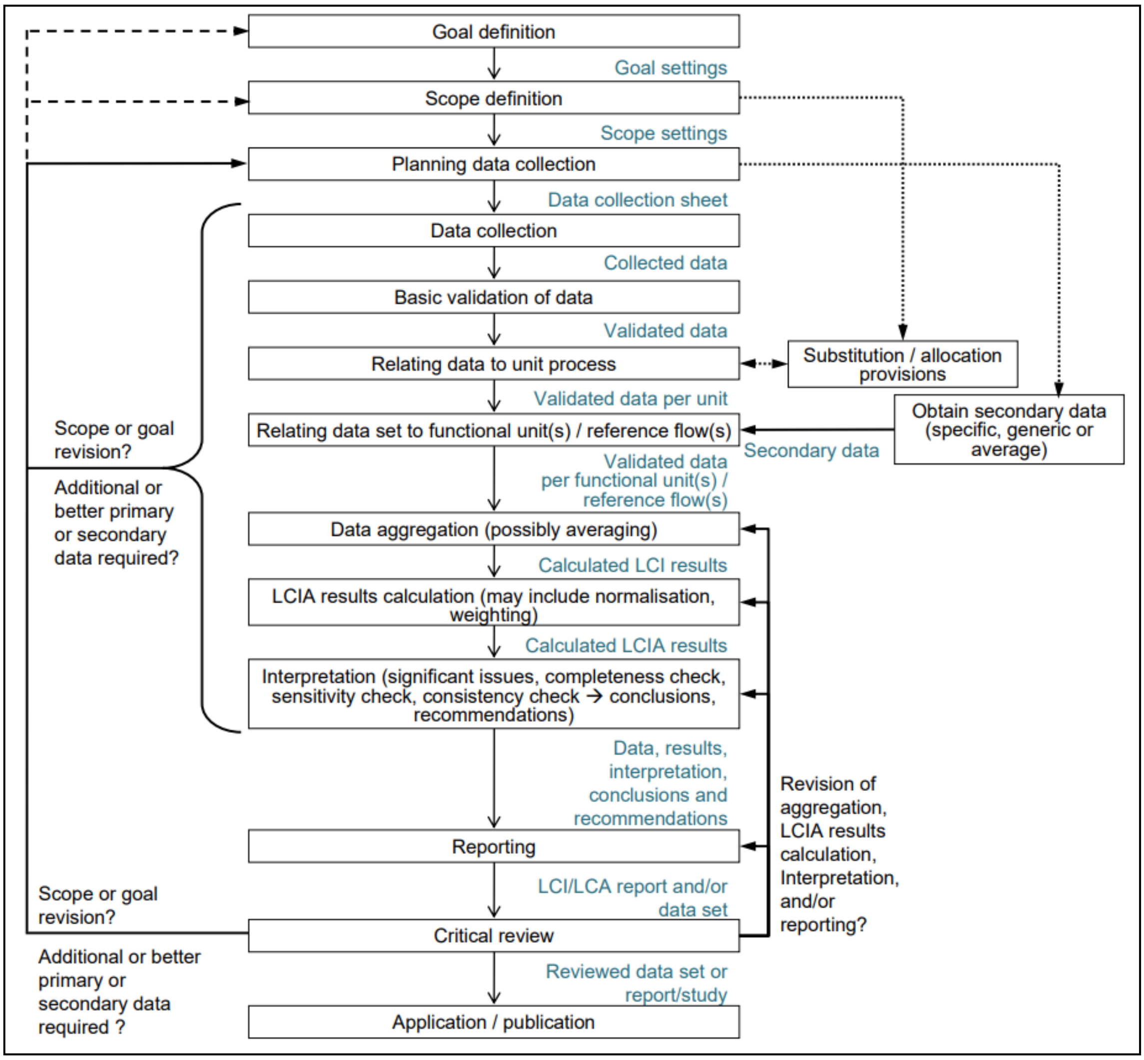

Figure 3. Details of the iterative approach to LCA, with focus on inventory data collection and modelling (from ISO 14044:2006, modified). Source: ILCD Handbook - General guide for Life Cycle Assessment - Detailed guidance (2010).

As previously stated, LCA studies rely on scenarios, assumptions, and simplifications that minimize the complexity of the system being studied while also introducing certain limits to LCA results. Due to the enormous quantity of data needed if basic data is absent and data collection does not represent the system under research, results may involve a larger uncertainty and the LCA study may not lead to reliable conclusions. Thus, LCA investigations rely on the capacity to collect primary or background data that appropriately describe the system under consideration.

This presented methodology has been used in all the works related with this research thesis. It has helped on identify important environmental hotspots of the different product systems under study, informing and assisting stakeholders and manufacturers in decisions aimed to improve the overall environmental performance. The LCA technique is also useful to compare the environmental performance of same function systems, comparing for instance new and conventional ones. Thus, helps on tracking primary environmental effects and benefits of various solutions, and supports critical decisions for process improvement (pollution prevention, resource consumption reduction, etc.).

3. Life Cycle Assessment for Metal Matrix Composites casting technologies.

The growth in the use of novel materials, as it is the case of the Metal Matrix Composites (MMCs), is producing a positive impact in production processes, allowing to obtain final products with improved functionalities, such as an increase of the strength-to-weight ratio, or enhancement of the mechanical properties of the material, minimizing as well the environmental impacts and production costs without compromising the required technical properties. To determine and compare the environmental impact of different processes employing these materials, this work provides a comparative analysis of the Life Cycle Assessment (LCA), under ISO 14040:2006 framework and European ILCD guidelines, of two different manufacturing technologies, Green Sand Casting (GSC) and Low Pressure Die Casting (LPDC), for the particular case of a self-cleaning doorknob, produced by an aluminium alloy reinforced with hard TiO2 nanoparticles, that confers special characteristics to the composite, such as an increase of the hardness value and tensile strength, a high wear resistance, a good chemical stability, and antibacterial properties. The results show a slight difference between both technologies in terms of kg CO2 eq. emitted, with just a 3,16 % variation, where GSC emissions are 13,098 kg, whereas 12,684 kg are released from LPDC. In addition, an economic analysis was performed, showing a 17 % cost reduction in case of LPDC. This study presents for the first time a comparative Life Cycle Assessment of GSC and LPDC, when employing new nanocomposite materials, contributing with novel datasets and meaningful insights to improve the state of the art in the field, serving as well as a support for manufacturers in decision making process involving the use of these technologies.

This work has been published in Ecological Indicators, Volume 144, under the following reference: *Santiago-Herrera, M. et al., 2022. Comparative life cycle assessment of green sand casting and low pressure die casting for the production of self-cleaning AlMg3-TiO2 metal matrix composite. Ecol. Indicat., 144 (2022), 109442, 10.1016/j.ecolind.2022.109442.*

3.1. Introduction.

In last decades, science and technology have extensively innovated in the development of new materials that could replace those traditionally used in different manufacturing sectors, where the requirements for lightweight, high strength, hard parts and other specific properties have increased (Naik et al., 2021; Bulei et al., 2020). At the same time, the use of alternative, newly developed materials might be a promising option as well from an environmental point of view, contributing to reduce greenhouse emissions and resources consumption (Ferreira et al., 2019), as it is the case of Metal Matrix Composites (MMCs).

MMCs consist of a base metal reinforced with one or more constituents, which can be any other material, either metal or non-metal, e.g. ceramics. These composite materials are characterized by a high strength-to-weight ratio, high thermal and wear resistance and good fatigue properties among others, with variable properties depending on their components (Vijaya Ramnath et al., 2021). The present study focuses on aluminium MMCs, based on an Al-Mg alloy, which is a standard strength structural alloy, commonly used because its good weldability, corrosion resistance, and immunity to stress corrosion cracking (Lata et al., 2018), and TiO2, known too as titanium oxide or titania, the naturally occurring oxide of titanium, as the reinforcing ceramic. TiO2 is an excellent option for MMCs due to its good hardness, low density, good strength, high melting point, high wear resistance, and good chemical stability (Irhayyim et al., 2019).

In addition, it is known that nanoparticles (NPs) of titanium dioxide have good photocatalytic properties and have been used as antiseptic and antibacterial component (Baskaran et al., 2015). Two types of phenomena happening on a TiO2 surface upon, following ultraviolet light irradiation: photocatalytic activity by photodegradation effects, and wetting ability induced by hydrophilicity, both accounting for the self-cleaning characteristics (Spanou et al., 2013). This process works in a passive way, with the only need of light and oxygen, being then non-poisonous and environmentally friendly (Liu et al., 2014; Fujishima et al., 2008).

Research on self-cleaning surfaces is currently a research area of high interest (Padmanabhan & John, 2020) for relevant applications in industrial environments, agriculture, military and daily-life activities, enabling different TiO2-based materials to eliminate bacteria under UV or visible irradiation, and remove contaminants by favouring the spread of water (Liu et al., 2014). TiO2 disinfection is also very effective, being 3 times stronger than that achieved with chlorine application, and 1.5 times stronger when compared to ozone (Iwatsu et al., 2020). In addition, recurrent cleaning with anti-bacterial chemicals can result in an environment where resistant bacteria could survive (Huang et al., 2000). It is also expected that self-cleaning TiO2 materials will have many medical applications, such as in body-internal implants or devices (Wachesk et al., 2021) or in tiles used in hospital room walls, medical instruments, and uniforms (Fujishima et al., 2008).

The materials with MMCs require the use of specific industrialized processes. For instance, casting process, which is one of the most energy demanding manufacturing methods specially caused by the melting step, which consumes more than a half of the total energy, typically produced employing fossil fuels. Moreover, increasing amounts of energy and materials are required to meet other specifications and steps, such as holding the liquid metal, moulding, or at the finishing phases (Pagone et al., 2018; Salonitis et al., 2017; Dalquist & Gutowski, 2004).

Industrial casting processes use sand as molding material and, in function on the binder used, they are classified as clay bonded sand (green sand) and chemically bonded sand methods (Khan et al., 2020). The present study focuses in part on the Green Sand Casting (GSC) method, which is a traditional process, and nowadays it is still considered as one of the basic processes for many manufacturing industries. This process starts with the fabrication of a sand mould, using patterns to get the desired design shape of the part to be cast. The sand mixed with water, bentonite and other additives is prepared, and the mould is made using the design pattern. Then, molten metal is poured into the sand mould cavity, and after solidification the material is removed by breaking the sand mould (Ranade et al., 2020).

The alternative production process involving the use of MMCs considered in the present study is known as Low Pressure Die Casting (LPDC). Currently, this is one of the dominant technologies, characterized by a high level of maturity (Ou et al., 2020), for the production of components with complex shapes (Sun et al., 2019). In this case, a die and a filling system are placed over a pressurized sealed melt furnaces, that contains the molten metal, which is forced by pressurized gas to rise and consequently feed the die cavity. Once the mould is filled and the molten metal has been completely solidified, the external pressure is released, and both the side and top dies are opened. Then, they can be closed again to repeat the cycle in the productive process (Ou et al., 2020; Merchán et al., 2019; Fu et al., 2008; Srinivasan et al., 2005).

Based on the above-discussed literature, the main objective of this study is to assess the environmental impact, following the established LCA methodology, of GSC and LPDC technologies for the production of an innovative MMC material, with self-cleaning characteristics, formed by an aluminium alloy reinforced with TiO2 nanoparticles.

To date, little research has been conducted on evaluating the overall performance of GSC and LPDC technologies, including emission characteristics, energy expenditure and environmental impacts, under the Life Cycle Assessment methodology. Only a similar work comparing both technologies was found (Salonitis et al., 2019), where an assessment of the embodied energy for different casting techniques (High Pressure Die Casting (HPDC), Low Pressure Die Casting (LPDC), and Low Pressure Sand Casting (LPSC)) was done to evaluate the performance of substitute traditional materials, showing an excess of energy utilisation on the sand casting technology. Regarding other previous studies reporting the environmental performance of the mentioned technologies, only works focusing on sand castings techniques, and just one using a Life Cycle Assessment approach, were found. In that particular study, LCA was applied, to compute the total environmental impact of the sand casting process during its manufacturing phase, comparing different available scenarios, overall showing that using renewable energy sources together with the introduction of some modifications in the sand casting process, such as reduction in resin, as well as sand and scrap recycling, results in a 67 % reduction in CO2 emissions (Yadav et al., 2021). Other works focused on sand sustainability, showing that a combination of recycled sand, up to 80 %, with different mixtures, have similar strength and permeability as fresh sand (Nargundkar & Shastri, 2020), or remarking the relevance of the binder type in the reprocessability of moulding sand (Khan et al., 2020). The efficiency of the process was also assessed in two different studies, one proposing a strategy based on a design parameter to eliminate sand casting defects, that translates into lower carbon emissions, higher efficiency and a more sustainable production, which reduced between 21 and 24 % of the carbon emissions (Zheng et al., 2020b); and a second one conducting an effectiveness analysis using new technologies of 3D printing for the mold making, resulting in a better resource utilization and in a reduction of the carbon emissions up to 20%, with significant production efficiencies (Zheng et al., 2020a). Another study showed that 3D printing techniques have the ability to create molds in less time, with much more complex geometries, avoiding defects inducted by the traditional semi-manual production (Rodríguez-Gonz´alez et al., 2019).

None of the previously published research studies focusing on the manufacturing processes mentioned above determine all relevant environmental and economic impacts, following a clear and concise methodology. Therefore, this study brings new light on the sustainability of GSC and LPDC, providing new data, such as energy and materials consumption, that was not publicly available to the date, using this information to conduct a comparative LCA. The obtained results, contributing with novel datasets and meaningful insights related to the environmental impact of the technologies under study, will support manufacturers in decision making processes involving their use.

As the interest in the development of new materials employing MMCs is growing, the evaluation of environmental impacts related to associated manufacturing techniques is a necessary step to create awareness about potential sustainability differences amongst them.

3.2. Case study.

Two different manufacturing lines (GSC and LPDC) owned by ÖGI (Österreichisches Gießerei-Institut - Austrian Foundry Research Institute), in pilot phase for the use of the novel MMC (AlMg3-TiO2), were studied to analyse their resources consumption, energy expenditure, waste production and final products. Fig. 4 and Fig. 5 display the GSC and LPDC, respectively.

The Green Sand Casting Process, as defined by ÖGI, entails the following processes: 1. Materials are introduced in an induction furnace; 2. Density and temperature control tests are carried out; 3. Gases are captured by a fume extractor to avoid high environmental impacts; 4. The material mix is transported with a crane hoist to be poured into the mold; 5. The sand (sand, water, bentonite clay and lustrous carbon) is prepared; 6. The sand is transported using a crane hoist; 7. A mold is created using sand by applying pressure, and the leftover is blown away; 8. The molten metal is poured into the mold; 9. The piece is unmoulded; 10. The sand could be recovered to be used again in the process;

11. Gases are captured by a fume extractor; 12. The final product is obtained after cooling.

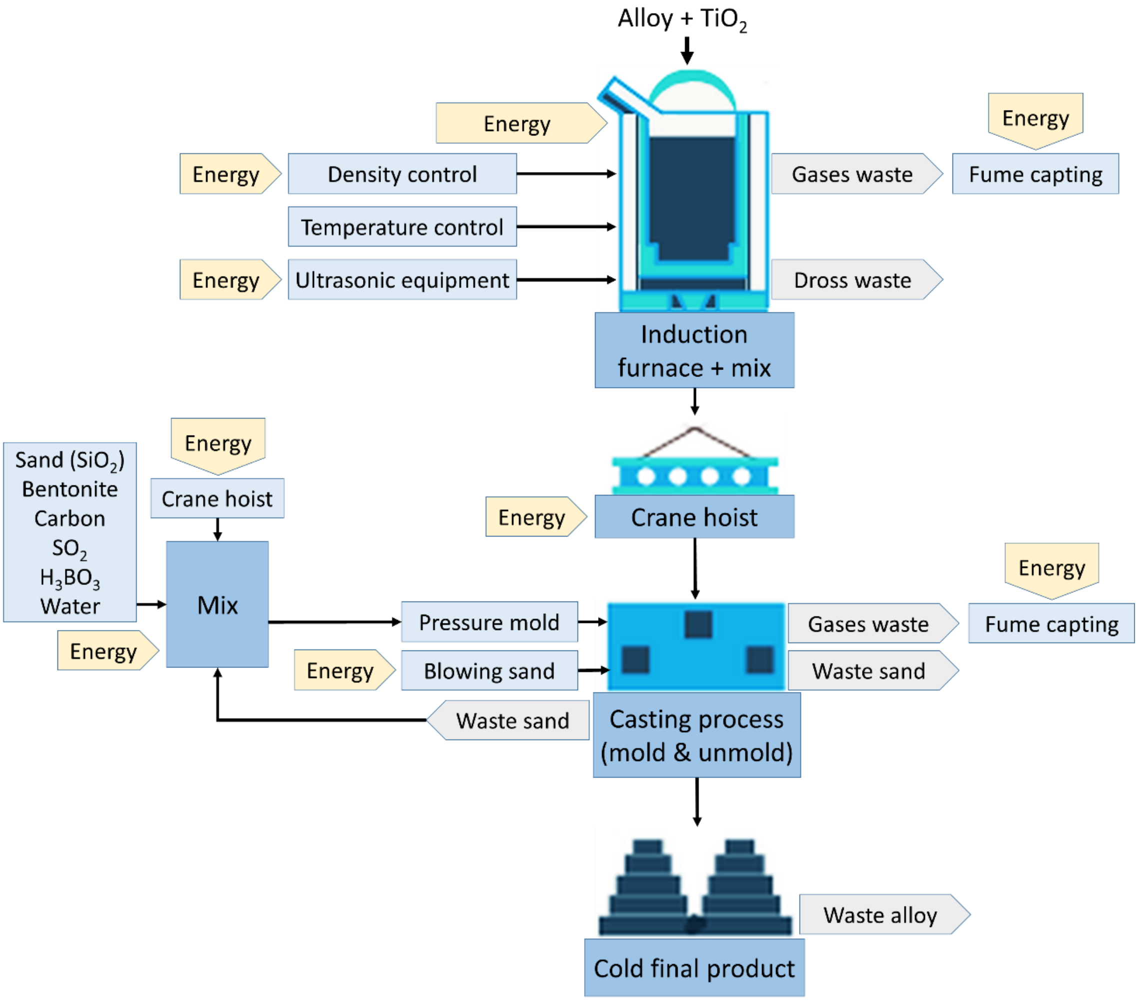

Figure 4. Green Sand Casting process flow diagram, defined by ÖGI. Source: Own elaboration.

The Low Pressure Die Casting process, as defined by ÖGI, entails the following processes: 1. Introduction of the alloy into the melting furnaces; 2. Degassing process using argon and a rotary unit; 3. Ultrasonic treatment; 4. Reduced pressure test is carried out; 5. Casting process; 6. Obtain of the final product.

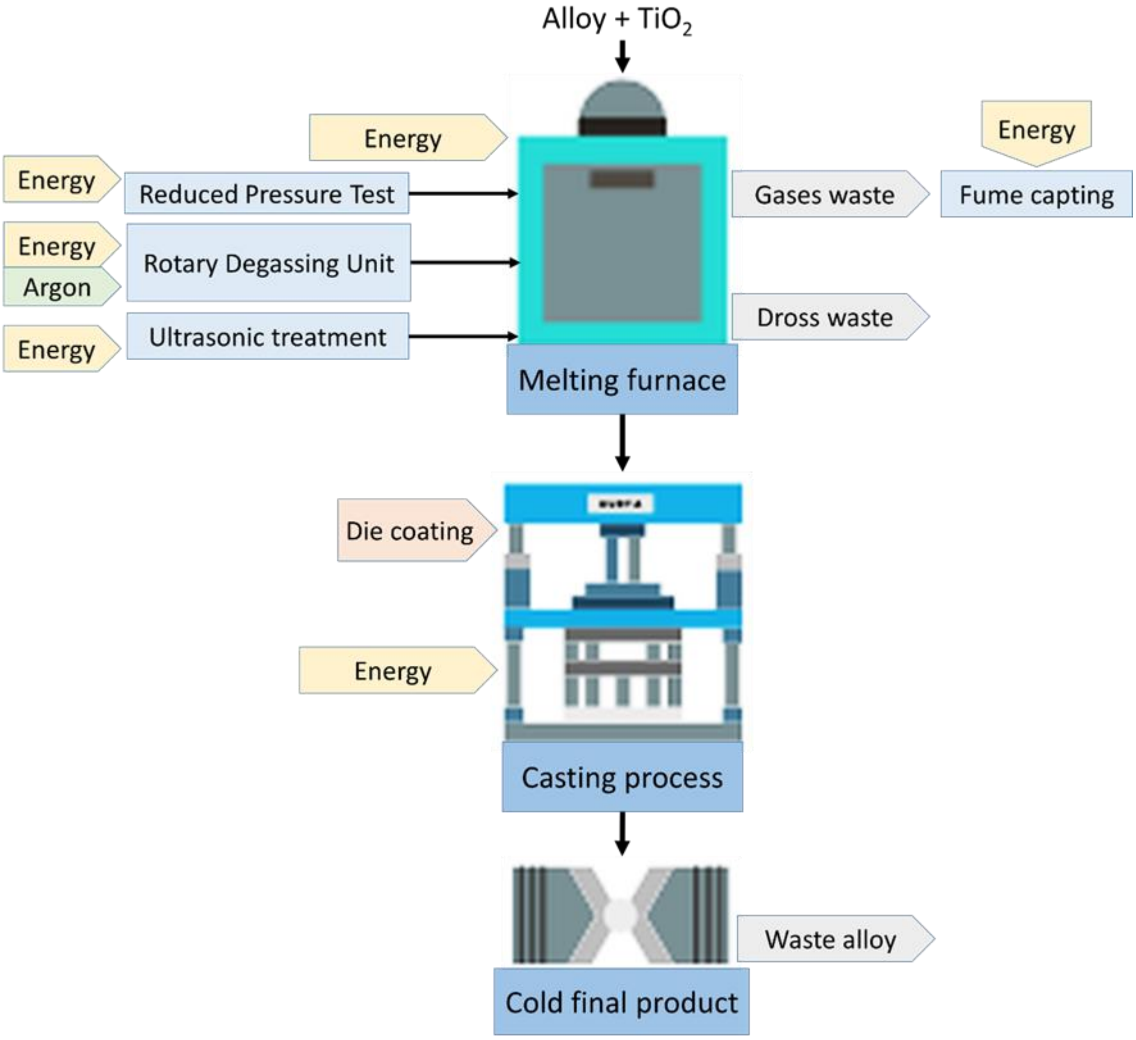

Figure 5. Low Pressure Die Casting process flow diagram, defined by ÖGI. Source: Own elaboration.

3.3. Methodology.

This study was conducted under the Environmental Life Cycle Assessment, also known as simply Life Cycle Assessment (LCA), which is a management tool to evaluate the environmental performance of products, goods and services. LCA considers a product's full life cycle, from the extraction of resources and the processing of raw materials, through production, use, possible recycling, to the final disposal of remaining waste (ISO, 2006b). In brief, LCA is a material and energy balance applied to the product's system, combined with an assessment of the environmental impacts related to the inputs and outputs of the product system. In this sense, LCA provides criteria for decision-making on issues such as product development, policymaking, and strategic planning, among others.

The LCA methodology to be used is according to the ISO framework (ISO, 2006) and referring to the recommendations and requirements given by the European ILCD guidelines (European Commission, 2010). In addition, the instructions included in *Life Cycle Assessment: Theory and Practice* (Hauschild et al., 2017) were used as a background to complete the study and methodology explanation. ISO 14040:2006 defines LCA as a technique for evaluating the environmental aspects and potential impacts associated with a product, by:

- Compiling an inventory of the relevant inputs and outputs within an appropriate system boundary.
- Evaluating the potential environmental impacts associated with those inputs and outputs.
- Interpreting the results of the inventory analysis and impact assessment phases with respect to the objectives of the study.

To achieve these purposes, information on inputs and outputs of the entire process need to be collected and processed. The standardised LCA framework comprehends four phases: (i) starting by the goal and scope definition to set the bases of the study, (ii) followed by an inventory analysis to collect all the relevant data within the system (material and energy flows), (iii) by the impact assessment, where the indicator results of all impact categories are detailed (iv), and finally by the interpretation (critical review and determination of data sensitivity) and presentation of results. These steps are clearly sequential, but most of the LCA studies follow an iterative process, to refine the obtained results, where the most relevant processes, resources and emissions receive a more specific attention.

The processes included in the system boundaries must be well delimited and all the different system choices within the analysis have to be properly justified, while the stages, processes and flows included in the study need to be well described. There are different system boundaries schemes, which depend on the data available:

- Cradle to cradle is a complete assessment which includes a reuse of the products.
- Cradle to grave extends the boundaries up to the disposal stage.
- Cradle to gate goes from the raw materials acquisition to the final production.
- Gate to gate only considers the production process.

3.3.1. Goal and scope.

As it was reflected in the Introduction section, the main aim of the LCA presented here is to inform about the environmental performance, through a comprehensive analysis, of the production process of self-cleaning doorknobs, using a MMC material formed by an aluminium alloy reinforced with TiO2 nanoparticles. Additional secondary objectives are related to provide economic and environmental arguments to easy decision making on the use of the different manufacturing technologies considered. Also, the study intends to provide life cycle inventory datasets that can contribute to enhance the state-of-the-art knowledge of GSC and LPDC. Both manufacturing techniques are modelled consistently, in terms of methodological choices and data selection, to obtain a fair and comparable representation of the two systems, complying with the ISO 14044:2006 requirements.

The production of one doorknob piece has been selected as the functional unit, which is appropriate to assess the different manufacturing systems, considering all the constraints. The selected functional unit is also useful for further study steps, which allow to determine materials and cleaning savings (e.g. cleaning products), due to the presence of NPs in the MMC alloy.

The present LCA study is a cradle-to-gate system boundary, given the information available, beginning with the introduction of the metal alloy and the nanoparticles to the manufacturing system, and finalizing with the obtention of the desired product. Only the inputs (raw materials, energy) and outputs (emissions, waste) associated with these core processes were included within the problem boundaries. Upstream activities (extraction, transportation) were included from data obtained in databases, while downstream activities (distribution, final use, disposal) were not considered in this study, but they could be included as new stages on a future study.

The database used for the analysis collect and integrate data from all the production stages of each input. The impacts from the upstream supply chain are also included in the assessment, as an average global approach. Further research would be necessary to collect more input data and properly assess these outbound steps. The transportation average values are assumed for the analysis in a similar way as mentioned above.

3.3.2. Life Cycle Inventory.

This stage is focused on the collection of data and the modelling of the flows, from and within the system, in line with the goal and scope definition.

Main data was provided by the technology owner, ÖGI, and other non-available information was extracted from literature and from LCA databases, such as ecoinvent v3.6 (Wernet et al., 2016), that allows for the use of georeferenced data and different allocation approaches. In particular, the APOS system model was adopted, that follows the attributional approach in which burdens are attributed proportionally to specific processes.

The only multifunctional process identified in this assessment was the recycling of the sand used for the mould in the GSC. This recycled process was clearly stated by the manufacturer, reusing the produced sand during 100 times, so the environmental impacts avoided by this circular process were introduced in the calculation. Also, the wood used to build the mold structure can be used many times too, so the quantity assumption was made based on the number of casts per working day and on the number of working days per year. No recycling of other raw material, like the metal alloy used, was implemented at this stage of the process.

Table 1 details, in a very comprehensive way, all the data specifications based on the volume of one full furnace, showing the raw materials, energy and other necessary items for the entire definition of the GSC and LPDC processes.

Table 1. Energy specifications for machinery and raw materials used in the GSC and LPDC.

GREEN SAND CASTING

Machinery, tools and other devices	Power (W)	Using time (h)	Total energy consumption (kWh)	Comments
Induction furnace	30000	6	180	heated for 6h. ingots melting 30min
Ultrasonic equipment	4500	0,17	0,75	in use 10 min
Density control device	300	0,07	0,02	in use 4 min
Fume capting	1500	7	10,5	during whole shift
Crane hoist	4000	0,17	0,67	in use 10 min
Sand mixer	15000	1	15	in use 60 min
Compressed air blowing system	15000	0,1	1,5	6 minutes per operation time

Materials	Quantity (kg)	Comments
AlMg3	49,5	-
TiO_2 (1%wt)	0,5	-
Sand (SiO_2)	100	-
Bentonite	0,1	-
Lustrous carbon	3,5	-
SO_2	0,05	-
H_3BO_3	0,1	-
Water	1	-
Membranes (filters, polyester cartridges)	0,0013636	0,3kg changed once a year, for 220 working days = 0,0013636 kg
Wood for mold structure	0,0098484	6,5kg of wood material for one double box (one cast part), that it can be used repeatedly, 3 casts during 220 working days -> 660 mold uses (made of multiplex board)

LOW PRESSURE DIE CASTING

Machinery, tools and other devices	Power (W)	Using time (h)	Total energy consumption (kWh)	Comments
Melting furnace	50000	6	300	heating 6h
Rotary degassing unit	560	0,75	0,42	in use 30 min to 1 hour
Ultrasonic equipment	4500	0,16	0,72	in use 10 min
Casting process LPDC	11000	6	66	casting 6h
Reduced pressure test	300	0,06	0,018	in use 4 min
Fume capting	1500	7	10,5	during whole shift

Materials	Quantity	Comments
AlMg3	148,5 kg	-
TiO_2 (1%wt)	1,5 kg	-
Argon	60 L	6L/min during 10 min
Die coating	0,5 kg	VESUVIUS DYCOTE D 39: Water based, zircon containing coatings
Membranes (filters, polyester cartridges)	0,0013636 kg	0,3kg, changed once a year, for 220 working days = 0,0013636 kg

The information displayed above was used for the assessment, based on the defined functional unit, allowing the determination of the environmental impact for each doorknob piece produced. In the case of the GSC, 20 casts can be made from 50 kg of metal introduced, obtaining a total of 40 doorknobs pieces. The LDPC can produced 125 doorknobs pieces from 150 kg introduced into the furnace. Tables showing this detailed information can be found in the Supplementary Material, Tables S1 and S2.

3.3.3. Life Cycle Impact Assessment (LCIA).

The Impact Assessment stage allows to transform the aforementioned Life Cycle Inventory data, collected in the previous section, into environmental impacts. To do that, a specific software was used to create the models for the impact assessment calculation: SimaPro® 9.1 by Pre' Consultants, which is one of the most commonly used LCA software. The selected impact assessment method was ILCD 2011 Midpoint, released in 2012 by the Joint Research Centre (JRC) of the European Commission (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2012), which constitutes a general basis for consistent life cycle data, methods and assessments, as it has been made with the aim to harmonize existing methodologies for LCIA. This method comprises 16 midpoint impact categories, based in different indicators from diverse authors, as shown in Table 2.

The specific characterization results of each of the technologies, showing the impacts produced by each of the inputs and different processes involved, can be found in the Supplementary Material, Tables S3, S4, S5 and S6. Table 3 presents an impact category characterization for comparison between GSC and LPDC.

According to ISO 14044:2006, normalization is an optional step where the systems' impacts are compared by relating them to a scale where they can be expressed in common units, which provide an impression of which of the environmental impact potentials are large and which are small, relative to the reference system, solving in this way the incompatibility of different units. The normalisation factors express the total impact occurring in a reference region for a certain impact category (e.g. climate change, eutrophication, etc.) within a reference year. The normalization factors in this assessment are based on Benini et al. (2014) and can be found in Supplementary Material, Figure S1.

Table 2. Impact categories of ILCD method.

Impact Category	Unit	Indicator	Reference
Climate change	kg CO_2 eq.	Global Warming Potential, calculating the radiative forcing over a time horizon of 100 years	IPCC's Fourth Assessment Report (IPCC, 2007)
Ozone depletion	kg CFC-11 eq.	Ozone Depletion Potential, measuring the destructive effects on the stratospheric ozone layer over a time horizon of 100 years	World Meteorological Organization (WMO, 1999)
Human toxicity, cancer effects	CTUh	Estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kilogramme)	USEtox model from Rosenbaum et al. (2008)
Human toxicity, non-cancer effects	CTUh	Estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kilogramme)	USEtox model from Rosenbaum et al. (2008)
Particulate matter	kg PM10 eq. to air	Premature death or disability that particulates/respiratory inorganics have on the population	RiskPoll software (Rabl & Spadaro, 2004) and Greco et al. (2007)
Ionizing radiation HH (human health)	kBq U235 eq.	Impact of ionizing radiation on the population, in comparison to Uranium 235	Frischknecht et al. (2000)
Ionizing radiation E (ecosystems)	PAF m^3 year/kg	Estimate of the potentially affected fraction of species integrated over time and volume per unit mass of a radionuclide emitted	Garnier-Laplace et al. (2009)
Photochemical ozone formation	NMVOC eq.	Potential contribution to photochemical ozone formation	van Zelm et al. (2008)
Acidification	mol H+ eq./kg	Change in critical load exceedance of the sensitive area in terrestrial and main freshwater ecosystems, to which acidifying substances deposit,	Seppälä et al. (2005) and Posch et al. (2008)
Terrestrial eutrophication	mol N eq.	Change in critical load exceedance of the sensitive area, to which eutrophying substances deposit	Seppälä et al. (2005) and Posch et al. (2008)
Freshwater eutrophication	kg P eq.	Degree to which the emitted nutrients reach the freshwater end compartment	ReCiPe model (Goedkoop et al., 2009)
Marine eutrophication	kg N eq.	Degree to which the emitted nutrients reach the marine end compartment	ReCiPe model (Goedkoop et al., 2009)
Freshwater ecotoxicity	CTUe	Estimate of the potentially affected fraction of species integrated over time and volume per unit mass of a chemical emitted	USEtox model from Rosenbaum et al. (2008)
Land use	kg $C/m^2/a$	Based on Soil Organic Matter	Milà i Canals et al. (2007)
Water resource depletion	m^3 water	Related to the freshwater scarcity	Swiss Ecoscarcity (Frischknecht et al., 2006)
Mineral, fossil & renewable resource depletion	kg Sb eq.	Scarcity of mineral identified resources that meets specified minimum physical and chemical criteria related to current mining practice	CML 2002 (Guinée et al., 2002)

Table 3. Impact category comparative characterization between GSC and LPDC.

Impact category	Unit	One doorknob by GSC	One doorknob by LPDC
Climate change	kg CO2 eq.	13,0978	12,6836
Ozone depletion	kg CFC-11 eq.	1,52E-06	1,47E-06
Human toxicity, non-cancer effects	CTUh	6,22E-06	5,96E-06
Human toxicity, cancer effects	CTUh	3,16E-06	3,03E-06
Particulate matter	kg PM2.5 eq.	0,0152	0,0146
Ionizing radiation HH	kBq U235 eq.	2,7174	2,6866
Ionizing radiation E (interim)	CTUe	7,23E-06	7,14E-06
Photochemical ozone formation	kg NMVOC eq.	0,0553	0,0532
Acidification	molc H+ eq.	0,0912	0,0878
Terrestrial eutrophication	molc N eq.	0,1590	0,1532
Freshwater eutrophication	kg P eq.	0,0078	0,0076
Marine eutrophication	kg N eq.	0,0161	0,0156
Freshwater ecotoxicity	CTUe	362,7360	330,6313
Land use	kg C deficit	21,0725	19,7512
Water resource depletion	m3 water eq.	0,0557	0,0604
Mineral, fossil & ren resource depletion	kg Sb eq.	0,0045	0,0043

In the assessment, weighting is a voluntary step as well, where the normalized results of each of the impact categories are multiplied by a weighting factor expressing the relative importance of the impact category. All the weighted results have the same unit and can be summed up to create one single score for the environmental impact. This helps decision making, because it clearly shows the most relevant impact categories, to ensure that the focus can be put on the important aspects of the assessment. The weighting factors in this assessment are based on the *Environmental Footprint Pilot Guidance document* (European Commission, 2014). Fig. 6 presents a single score comparative between both manufacturing technologies. Table S7 in the Supplementary Material shows the associated data.

Another important factor to compare is the total energy consumption, with implications for the generation of environmental impacts, which accounts for 5,228 kWh in GSC and 3,021 kWh in LPDC.

To improve the assessment, aiming to enhance the comparison possibilities, a cost analysis was carried out as well, supported by data obtained from the technology owner (ÖGI), such as the capital and operational expenditures, indirect costs, operative and production time, and labour force expenses. The data analysis performed shows a total unit cost of 11,12€ in the case of GSC, and 9,23€ in the case of LPDC, for the production of one doorknob. The data employed in the cost analysis can be found in the Supplementary Material, Table S9. The economic data, together with the environmental impacts extracted from the weighting analysis, makes possible to draw a comparison matrix chart that facilitates the interpretation of results (Fig. 7).

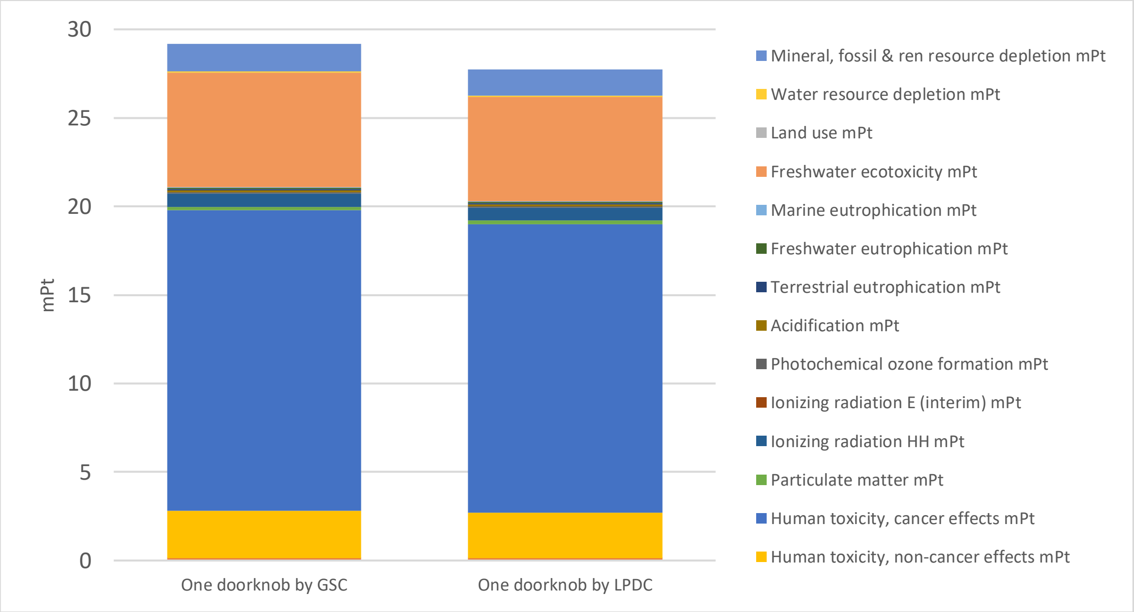

Figure 6. Weighting (single score) comparative between GSC and LPDC.

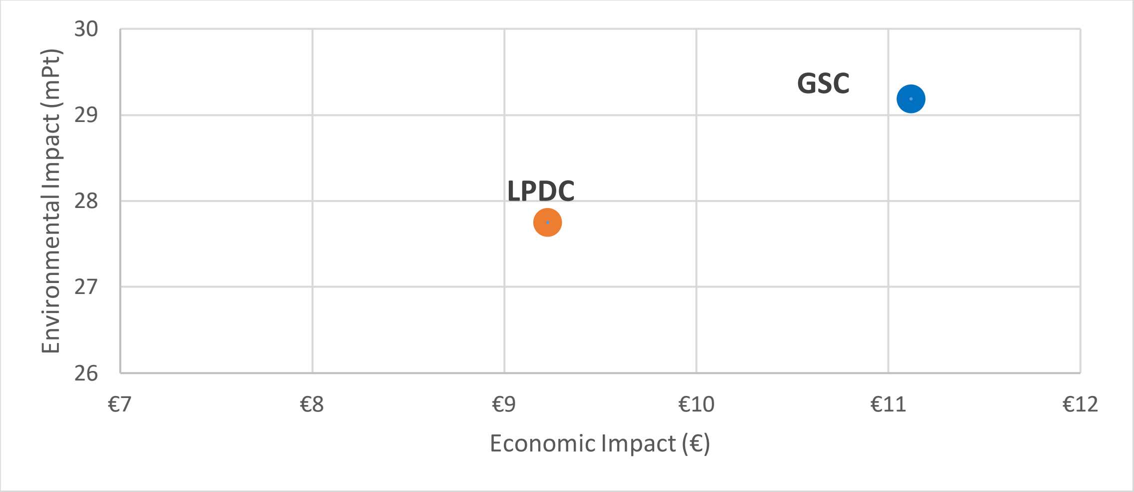

Figure 7. Comparison matrix chart of both technologies, GSC and LPDC, with the environmental impact measured in mPt and the economic impact measured in €.

3.3.4. Sensitivity analysis.

Further developments of the assessed technologies are expected, which are likely to improve their environmental performance. A possibility could be to recycle the metal excess from the mold which is removed from the final part. Considering this, an assessment based on expected reusing of the waste alloy derived from the process, introduced again in a hypothetical closed-loop system, has been undertaken as a sensitivity analysis. Changes on the energy consumption were not contemplated due to lack of data, although an improvement on this aspect is probable as well. Table 4 shows the impact category characterization for the new scenario, and Fig. 8 displays a comparison with the respective initial scenarios. The weighting score for this assessment can be found in the Supplementary Material, Table S8.

Table 4. Impact category comparative characterization between GSC and LPDC under a potential reusing scenario.

Impact category	Unidad	One doorknob by GSC (with alloy reusing scenario)	One doorknob by LPDC (with alloy reusing scenario)
Climate change	kg CO2 eq.	2,869	2,886
Ozone depletion	kg CFC-11 eq.	3,46E-07	3,51E-07
Human toxicity, non-cancer effects	CTUh	1,19E-06	1,14E-06
Human toxicity, cancer effects	CTUh	3,63E-07	3,58E-07
Particulate matter	kg PM2.5 eq.	0,002	0,002
Ionizing radiation HH	kBq U235 eq.	1,307	1,336
Ionizing radiation E (interim)	CTUe	3,39E-06	3,47E-06
Photochemical ozone formation	kg NMVOC eq.	0,008	0,008
Acidification	molc H+ eq.	0,017	0,017
Terrestrial eutrophication	molc N eq.	0,027	0,027
Freshwater eutrophication	kg P eq.	0,003	0,003
Marine eutrophication	kg N eq.	0,003	0,003
Freshwater ecotoxicity	CTUe	96,318	75,445
Land use	kg C deficit	3,835	3,241
Water resource depletion	m3 water eq.	0,025	0,031
Mineral, fossil & ren resource depletion	kg Sb eq.	2,62E-04	2,65E-04

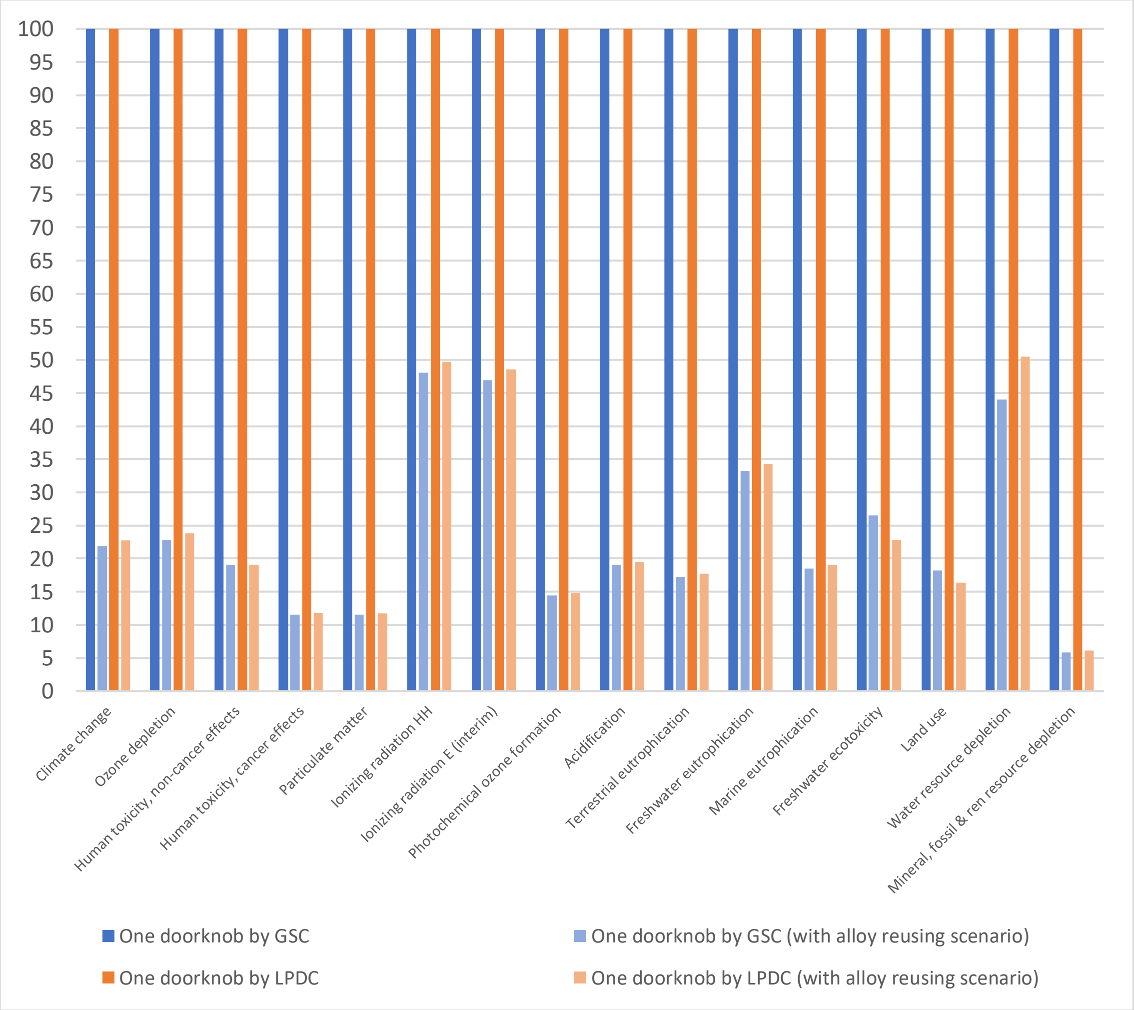

Figure 8. Impact category comparative characterization results between GSC and LPDC with their respective potential reusing scenario.

3.3.5. Life Cycle Interpretation.

In this phase, the collected data and the outcome of the assessment done are considered and analysed together, to present the conclusions of the study. In regard of the impacts determined by the analysis, the LCA assessment shows that the production of one doorknob by GSC generates more impacts than by LPDC, but the difference is small. For instance, considering the climate change category, measured in kg CO2 eq., 13,098 kg are emitted by GSC, whereas 12,684 kg are released by LPDC, meaning just a 3,16 % variation. Water resource depletion is the sole impact category where LPDC produces higher impact, most likely due to the use of argon in the process.

The normalization analysis illustrates that the impact category with the biggest magnitude is the Human toxicity, with cancer effects, followed by the Freshwater ecotoxicity. Also, Human toxicity, non-cancer effects, Mineral fossil & ren. resource depletion and Ionizing radiation have a significant impact. Considering the weighting score, expressed in mPt units, LPDC with 27,749 mPt reduces in a 4,915 % the impacts caused by GSC, with 29,183 mPt.

In case of the economic aspects, the difference between both technologies shows a 17 % reduction on the price when using the LPDC. Among the processes' steps, the one that has the greatest impact on the final cost is the melting of the material in both pilot plants, which accounts for the 70 % of the cost in the GSC plant, and 78 % in the LPDC plant. The great impact of this process derives from the high cost of TiO2, whose current price is 158€ per kilogram, as well as the long time that takes to carry out this activity.

With the new scenario proposed for the sensivity analysis a significant reduction of impacts is achieved. All the impact categories are reduced for more than a 50 %, reaching in some cases (Mineral, fossil & ren. resource depletion) a reduction higher than 90 %. Regarding the kg CO2 eq. emitted there is a reduction of 78,095 % in the case of the GSC and of 77,246 % for the LPDC. Considering the weighting score, the reduction is an 83,603 % for the GSC and 84,218 % for the LPDC, compared with the initial scenarios.

Some assumptions and limitations applied, as described in *Goal and Scope* and *Inventory* sections, mainly related with the system study boundaries, could vary the final outcome results. For instance, a scope extension without including the use and disposal phase does not show a full life cycle analysis and possible benefits after implementation, but as the production is not completely optimized yet, these data could not be obtained and assessed. The use of global average approach from databases instead of primary transport data, which was not available, differs more from a realistic scenario, probably slightly increasing some of the impacts. Also, an average for European electricity could hide impacts from different electricity mixes depending on the country.

To summarize, the main issue identified, causing the highest quantity of environmental impacts, is related with the extraction and production of aluminium, used for the alloy. Other important factors are the use of electricity for both processes, and the use of argon in LPDC.

3.4. Conclusions.

After the complete assessment it is evident that the production of one doorknob produces less environmental impact if its manufactured by LPDC instead of GSC, but only achieving a reduction of approximately 5 %, measured under the weighting single score scale. However, in the economic assessment, a reduction of 17 % of the total production cost can be reached.

The extraction, production and use of the aluminium alloy is the most impactful process within both manufacturing technologies, but the quantities introduced are very similar, so this does not translate in an impact difference. However, the energy expenditure is more than a 40 % lower in LPDC than in GSC. Still, the impact produced by this difference is reduced due to the use of argon in LPDC. Also, the components used for the sand manufacturing in GSC are not very critical, and can be recycled at 92,5% a total of 100 times, so the associated impacts are very low.

Observing the normalization results, Human toxicity, with cancer effects and Freshwater ecotoxicity are the most important categories. These effects are produced during the aluminium extraction and the production of the alloy, which are very pollutant. It is also worth mentioning that in case of the TiO_2 nanoparticles the main impact category is the Freshwater ecotoxicity.

Regarding the alternative scenario including the reutilization of the alloy, a significant potential reduction on the impacts was expected, and after the assessment it was determined that more than 80 % of the impacts, for both manufacturing processes, could be avoided by reusing the alloy material. A higher reduction could be expected after and optimization of the energy use, or by recirculating the used argon in case of LPDC.

While the environmental assessment can identify the hotspots where most of the impacts are caused, the cost analysis implemented is valid to find the most expensive processes, linking them with the environmental impacts, permitting to determine in global terms the most sustainable option from an economic point of view, which is of great interest for manufacturers.

The assumptions made during the modelling phase have low relevance in the final outcomes, but it was still necessary to address them, together with the system limits, for helping on potential future replications of the study. Further data and analyses would be necessary to evaluate other parts of the supply chain, in order to get a full assessment of the life cycle of the products obtained through these technologies. For instance, benefits related with the use phase of the antibacterial doorknobs, producing savings in cleaning products, are expected. However, the effects of the disposal phase are less clear, because the impact associated to the treatment of the produced metal residues containing nanoparticles is still under research and debate.

The production processes, environmental impacts, and costs disclosed in this research for GSC and LPDC, provides novel and meaningful data and insights, accessible for researchers, manufactures and designers, helping them in decision making when selecting manufacturing technologies employing advanced MMCs.

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3.6. Supplementary information for Chapter 5.

Table S1. Inventory for the production of one doorknob by Green Sand Casting.

PROCESSES IDENTIFIED				
Process 1 - Induction furnace + mixing + temperature control				
Materials	**Unit**	**Quantity**	**Comments**	**ecoinvent database Reference**
Inputs				
AlMg3	kg	1,2375	/	Aluminium alloy, AlMg3 {GLO}| market for | APOS, U
TiO_2 (1%wt)	kg	0,0125	/	Titanium dioxide {RER}| market for | APOS, U
Electricity consumption	kWh	4,5	/	Electricity, low voltage {Europe without Switzerland} | market group for | APOS, U
Outputs				
Dross	kg	0,01875	1-2% dross (1,5%)	/
Melted alloy	kg	1,23125	/	/
Process 2 - Ultrasonic equipment				
Materials	**Unit**	**Quantity**	**Comments**	**ecoinvent database Reference**
Inputs				
Electricity consumption	kWh	0,01875	/	Electricity, low voltage {Europe without Switzerland} | market group for | APOS, U
Process 3 - Density control				
Materials	**Unit**	**Quantity**	**Comments**	**ecoinvent database Reference**
Inputs				
Alloy	kg	0,002	very low quantity, no considered in the process	/
Electricity consumption	kWh	0,0005	/	Electricity, low voltage {Europe without Switzerland} | market group for | APOS, U
Process 4 - Fume capting				
Materials	**Unit**	**Quantity**	**Comments**	**ecoinvent database Reference**
Inputs				
Membranes (filters)	kg	0,0000341	changed once a year	Fibre, polyester {GLO}| market for fibre, polyester | APOS, U
Electricity consumption	kWh	0,26250	used during whole shift	Electricity, low voltage {Europe without Switzerland} | market group for | APOS, U
Process 5 - Crane hoist (alloy)				
Materials	**Unit**	**Quantity**	**Comments**	**ecoinvent database Reference**
Inputs				
Electricity consumption	kWh	0,01667	/	Electricity, low voltage {Europe without Switzerland} | market group for | APOS, U
Process 6 - Sand preparation				
Materials	**Unit**	**Quantity**	**Comments**	**ecoinvent database Reference**
Inputs				
Sand (SiO2)	kg	2,500	95,465%	Silica sand {GLO}| market for | APOS, U
Bentonite	kg	0,0025	0,095%	Activated bentonite {GLO}| market for | APOS, U
Lustrous carbon	kg	0,0875	3,341%	Activated carbon, granular {GLO}| market for activated carbon, granular | APOS, U
SO2	kg	0,00125	0,048%	Sulfur dioxide, liquid {RER}| market for | APOS, U
H3BO3	kg	0,0025	0,095%	Boric acid, anhydrous, powder {GLO}| market for | APOS, U
Water	kg	0,025	0,955%	Water, deionised {Europe without Switzerland} | market for water, deionised | APOS, U
Outputs				
Sand	kg	2,61875	quantity for 20 double boxes (20 casting parts), needed to cast the entire furnace volume	/
Process 7 - Mixing (sand)				
Materials	**Unit**	**Quantity**	**Comments**	**ecoinvent database Reference**
Inputs				
Sand	kg	3,5	max. volume introduced in the mixer	/
Electricity consumption	kWh	0,375	1 hour process	Electricity, low voltage {Europe without Switzerland} | market group for | APOS, U
Outputs				
Remained sand	kg	0,88125	remain in the mixer for the next 100 cycles	/
Mixed Sand	kg	2,61875	/	/
Process 8 - Crane hoist (sand)				
Materials	**Unit**	**Quantity**	**Comments**	**ecoinvent database Reference**
Inputs				
Electricity consumption	kWh	0,0167	/	Electricity, low voltage {Europe without Switzerland} | market group for | APOS, U
Process 9 - Pressure mold manufacture				
not in use for the project				
Process 10 - Blowing leftover sand				
Materials	**Unit**	**Quantity**	**Comments**	**ecoinvent database Reference**
Inputs				
Electricity consumption	kWh	0,0375	during whole shift	Electricity, low voltage {Europe without Switzerland} | market group for | APOS, U
Process 11-Molds&Unmolds (casting)				
Materials	**Unit**	**Quantity**	**Comments**	**ecoinvent database Reference**
Inputs				
Material for the mold structure (wood)	kg	0,000246	6,5kg of wood material for one double box (one cast part), it can be used again and again, supposing a one labour year life, 3 cast by 220 working days -> 660 mold uses	Plywood, for outdoor use {RER}| market for | APOS, U
Melted alloy	kg	1,23125	/	/
Electricity consumption	kWh	/	/	Electricity, low voltage {Europe without Switzerland} | market group for | APOS, U
Outputs				
Final cast doorknob	kg	0,064	1,92kg introduced per cast, 20 casts, 2 pieces of 0,064kg, final weight before machining	/
Wasted alloy	kg	1,16725	/	/
Recycled sand	kg	2,39812	92,5% recycled (reuse 100 cycles, so multiplied by 99%)	/
Wasted sand	kg	0,22062	5-10% wasted (so 7,5%), rest is reuse for 100 cycles (so multiplied by 99%, and total kgs introduced as primary sand are added are total waste at the end)	/

Table S2. Inventory for the production of one doorknob by Low Pressure Die Casting

PROCESSES IDENTIFIED				
Process 1 - Melting furnaces				
Materials	**Unit**	**Quantity**	**Comments**	**ecoinvent database Reference**
Inputs				
AlMg3	kg	1,188	/	Aluminium alloy, AlMg3 {GLO}| market for | APOS, U
TiO2 (1%wt)	kg	0,012	/	Titanium dioxide {RER}| market for | APOS, U
Electricity consumption	kWh	2,4	for heating during 6h	Electricity, low voltage {Europe without Switzerland} | market group for | APOS, U
Outputs				
Melted alloy	kg	1,08	/	/
Wasted alloy	kg	0,12	10% loss	/
Process 2 - Rotary degassing unit				
Materials	**Unit**	**Quantity**	**Comments**	**ecoinvent database Reference**
Inputs				
Argon	l	0,48	6L/min during 10 min	Argon, liquid {RER}| market for argon, liquid | APOS, U
Electricity consumption	kWh	0,00336	during 30min to 1 hour, 45min	Electricity, low voltage {Europe without Switzerland} | market group for | APOS, U
Process 3 - Ultrasonic treatment				
Materials	**Unit**	**Quantity**	**Comments**	**ecoinvent database Reference**
Inputs				
Electricity consumption	kWh	0,00576	/	Electricity, low voltage {Europe without Switzerland} | market group for | APOS, U
Process 4 - Casting process LPDC				
Materials	**Unit**	**Quantity**	**Comments**	**ecoinvent database Reference**
Inputs				
Melted alloy	kg	1,08	30kg (80% yield for the whole process) for waste	/
Die coating	kg	0,004	Water based, zircon containing coatings (VESUVIUS DYCOTE D 39)	Zircon, 50% zirconium {GLO}| market for | APOS, U
Electricity consumption	kWh	0,528	during 6h	Electricity, low voltage {Europe without Switzerland} | market group for | APOS, U
Outputs				
Final cast doorknob	kg	0,064	1.92 cast piece, 0.064 doorknob, 1.792 to waste	/
Remained alloy	kg	0,12	15 kg remain	/
Wasted alloy	kg	0,896	/	/
Process 5 - Reduced pressure test				
Materials	**Unit**	**Quantity**	**Comments**	**ecoinvent database Reference**
Inputs				
Melted alloy	kg	0,00064	very low quantity, no consider in the process	/
Electricity consumption	kWh	0,000144	/	Electricity, low voltage {Europe without Switzerland} | market group for | APOS, U
Process 6 – Fume capting				
Materials	**Unit**	**Quantity**	**Comments**	**ecoinvent database Reference**
Inputs				
Membranes (filters)	kg	0,0000109	changed once a year	Fibre, polyester {GLO}| market for fibre, polyester | APOS, U
Electricity consumption	kWh	0,08400	used during whole shift	Electricity, low voltage {Europe without Switzerland} | market group for | APOS, U
Membranes (filters)	kg	0,0000109	/	/

Table S3. Characterization of environmental impacts from materials used in the GSC.

Impact category	Unit	Total	AlMg3	TiO2	Filters	Sand	Bentonite	Carbon	SO2	H3BO3	Water	Wood	Electricity	(r) Sand	(r) Bentonite	(r) Carbon	(r) SO2	(r) H3BO3	(r) Water
Climate change	**kg CO2 eq**	1,3E+01	1,1E+01	6,9E-02	1,4E-04	1,2E-01	1,3E-03	2,8E-01	4,3E-04	2,4E-03	-5,6E-06	-5,9E-04	2,3E+00	-1,1E-01	-1,2E-03	-2,6E-01	-3,8E-04	-2,2E-03	5,1E-06
Ozone depletion	**kg CFC-11 eq**	1,5E-06	1,2E-06	7,6E-09	7,7E-12	1,2E-08	2,4E-10	8,6E-09	4,9E-11	2,2E-10	5,1E-12	2,6E-11	2,8E-07	-1,1E-08	-2,2E-10	-7,8E-09	-4,3E-11	-2,0E-10	-4,7E-12
Human toxicity, non-cancer effects	**CTUh**	6,2E-06	5,3E-06	2,9E-08	3,2E-11	2,6E-08	6,0E-10	5,9E-08	2,7E-10	1,7E-09	4,1E-12	1,2E-10	9,1E-07	-2,4E-08	-5,5E-10	-5,4E-08	-2,4E-10	-1,6E-09	-3,7E-12
Human toxicity, cancer effects	**CTUh**	3,2E-06	2,9E-06	2,1E-08	7,3E-12	4,3E-09	9,2E-11	1,3E-08	4,6E-11	1,9E-10	1,1E-12	1,1E-11	2,1E-07	-3,9E-09	-8,5E-11	-1,2E-08	-4,0E-11	-1,7E-10	-9,7E-13
Particulate matter	**kg PM2.5 eq**	1,5E-02	1,4E-02	9,0E-05	9,1E-08	1,3E-04	1,5E-06	3,1E-04	4,5E-06	5,8E-06	8,6E-09	9,9E-07	1,0E-03	-1,2E-04	-1,4E-06	-2,8E-04	-4,0E-06	-5,4E-06	-7,9E-09
Ionizing radiation HH	**kBq U235 eq**	2,7E+00	1,5E+00	7,9E-03	1,0E-05	5,0E-03	1,1E-04	1,3E-02	1,4E-04	2,0E-04	1,0E-06	3,3E-05	1,2E+00	-4,6E-03	-1,0E-04	-1,2E-02	-1,2E-04	-1,8E-04	-9,4E-07
Ionizing radiation E (interim)	**CTUe**	7,2E-06	4,0E-06	2,6E-08	3,6E-11	3,0E-08	4,2E-10	4,3E-08	3,9E-10	8,4E-10	3,3E-12	1,1E-10	3,2E-06	-2,8E-08	-3,8E-10	-3,9E-08	-3,4E-10	-7,8E-10	-3,0E-12
Photochemical ozone formation	**kg NMVOC eq**	5,5E-02	5,0E-02	2,8E-04	6,4E-07	7,1E-04	6,0E-06	8,3E-04	6,8E-06	2,0E-05	2,9E-08	1,2E-06	5,3E-03	-6,5E-04	-5,5E-06	-7,6E-04	-6,0E-06	-1,9E-05	-2,7E-08
Acidification	**molc H+ eq**	9,1E-02	7,6E-02	1,4E-03	6,5E-07	9,7E-04	1,2E-05	2,0E-03	8,8E-05	4,7E-05	8,9E-08	1,6E-06	1,3E-02	-8,9E-04	-1,1E-05	-1,9E-03	-7,7E-05	-4,3E-05	-8,2E-08
Terrestrial eutrophication	**molc N eq**	1,6E-01	1,4E-01	8,3E-04	1,3E-06	2,6E-03	2,0E-05	3,0E-03	4,7E-06	7,3E-05	9,5E-08	5,1E-06	2,0E-02	-2,4E-03	-1,8E-05	-2,7E-03	-4,1E-06	-6,7E-05	-8,7E-08
Freshwater eutrophication	**kg P eq**	7,8E-03	5,5E-03	2,9E-05	4,1E-08	2,3E-05	7,7E-07	1,2E-04	3,3E-07	1,0E-06	3,7E-09	7,6E-08	2,3E-03	-2,1E-05	-7,1E-07	-1,1E-04	-2,9E-07	-9,3E-07	-3,4E-09
Marine eutrophication	**kg N eq**	1,6E-02	1,4E-02	9,1E-05	1,4E-07	2,4E-04	1,7E-06	2,9E-04	4,7E-07	6,6E-06	9,5E-09	3,5E-07	2,2E-03	-2,2E-04	-1,6E-06	-2,6E-04	-4,1E-07	-6,0E-06	-8,7E-09
Freshwater ecotoxicity	**CTUe**	3,6E+02	2,8E+02	1,6E+00	2,0E-03	8,0E-01	4,0E-02	1,6E+00	2,2E-02	1,1E-01	2,4E-04	3,6E-03	8,2E+01	-7,3E-01	-3,7E-02	-1,4E+00	-2,0E-02	-9,8E-02	-2,2E-04
Land use	**kg C deficit**	2,1E+01	1,8E+01	1,4E-01	1,3E-04	3,3E+00	5,2E-03	2,0E-01	1,0E-03	5,8E-03	2,0E-05	4,5E-03	2,6E+00	-3,0E+00	-4,8E-03	-1,9E-01	-9,2E-04	-5,3E-03	-1,9E-05
Water resource depletion	**m3 water eq**	5,6E-02	3,2E-02	5,4E-04	2,6E-07	1,2E-04	2,9E-06	-3,2E-04	2,8E-06	2,8E-06	3,5E-06	1,0E-06	2,3E-02	-1,1E-04	-2,7E-06	2,9E-04	-2,5E-06	-2,6E-06	-3,2E-06
Mineral, fossil & ren resource depletion	**kg Sb eq**	4,5E-03	4,4E-03	4,5E-05	2,8E-09	1,7E-06	1,9E-07	6,4E-07	3,8E-08	9,5E-07	3,1E-10	4,9E-09	3,2E-05	-1,6E-06	-1,8E-07	-5,9E-07	-3,4E-08	-8,7E-07	-2,8E-10

Table S4. Characterization of environmental impacts from processes used in the GSC.

Impact category	Unit	Total	Process 1	Process 2	Process 3	Process 4	Process 5	Process 6	Process 7	Process 8	Process 9	Process 10	Process 11
Climate change	**kg CO2 eq**	**1,3E+01**	1,3E+01	8,2E-03	2,2E-04	1,1E-01	7,3E-03	3,5E-02	1,6E-01	7,3E-03	0	1,6E-02	-5,9E-04
Ozone depletion	**kg CFC-11 eq**	**1,5E-06**	1,5E-06	1,0E-09	2,7E-11	1,4E-08	9,0E-10	1,7E-09	2,0E-08	9,0E-10	0	2,0E-09	2,6E-11
Human toxicity, non-cancer effects	**CTUh**	**6,2E-06**	6,1E-06	3,3E-09	8,7E-11	4,6E-08	2,9E-09	7,4E-09	6,5E-08	2,9E-09	0	6,5E-09	1,2E-10
Human toxicity, cancer effects	**CTUh**	**3,2E-06**	3,1E-06	7,6E-10	2,0E-11	1,1E-08	6,7E-10	1,5E-09	1,5E-08	6,7E-10	0	1,5E-09	1,1E-11
Particulate matter	**kg PM2.5 eq**	**1,5E-02**	1,5E-02	3,6E-06	9,5E-08	5,0E-05	3,2E-06	3,9E-05	7,1E-05	3,2E-06	0	7,1E-06	9,9E-07
Ionizing radiation HH	**kBq U235 eq**	**2,7E+00**	2,5E+00	4,4E-03	1,2E-04	6,2E-02	3,9E-03	1,6E-03	8,8E-02	3,9E-03	0	8,8E-03	3,3E-05
Ionizing radiation E (interim)	**CTUe**	**7,2E-06**	6,8E-06	1,1E-08	3,0E-10	1,6E-07	1,0E-08	6,3E-09	2,3E-07	1,0E-08	0	2,3E-08	1,1E-10
Photochemical ozone formation	**kg NMVOC eq**	**5,5E-02**	5,4E-02	1,9E-05	5,0E-07	2,7E-04	1,7E-05	1,3E-04	3,8E-04	1,7E-05	0	3,8E-05	1,2E-06
Acidification	**molc H+ eq**	**9,1E-02**	8,9E-02	4,7E-05	1,3E-06	6,6E-04	4,2E-05	2,7E-04	9,4E-04	4,2E-05	0	9,4E-05	1,6E-06
Terrestrial eutrophication	**molc N eq**	**1,6E-01**	1,6E-01	7,1E-05	1,9E-06	1,0E-03	6,3E-05	4,8E-04	1,4E-03	6,3E-05	0	1,4E-04	5,1E-06
Freshwater eutrophication	**kg P eq**	**7,8E-03**	7,5E-03	8,2E-06	2,2E-07	1,2E-04	7,3E-06	1,3E-05	1,6E-04	7,3E-06	0	1,6E-05	7,6E-08
Marine eutrophication	**kg N eq**	**1,6E-02**	1,6E-02	8,0E-06	2,1E-07	1,1E-04	7,1E-06	4,5E-05	1,6E-04	7,1E-06	0	1,6E-05	3,5E-07
Freshwater ecotoxicity	**CTUe**	**3,6E+02**	3,5E+02	2,9E-01	7,8E-03	4,1E+00	2,6E-01	2,1E-01	5,9E+00	2,6E-01	0	5,9E-01	3,6E-03
Land use	**kg C deficit**	**2,1E+01**	2,0E+01	9,4E-03	2,5E-04	1,3E-01	8,3E-03	2,9E-01	1,9E-01	8,3E-03	0	1,9E-02	4,5E-03
Water resource depletion	**m3 water eq**	**5,6E-02**	5,3E-02	8,2E-05	2,2E-06	1,1E-03	7,3E-05	-1,6E-05	1,6E-03	7,3E-05	0	1,6E-04	1,0E-06
Mineral, fossil & ren resource depletion	**kg Sb eq**	**4,5E-03**	4,5E-03	1,1E-07	3,1E-09	1,6E-06	1,0E-07	2,9E-07	2,3E-06	1,0E-07	0	2,3E-07	4,9E-09

Table S5. Characterization of environmental impacts from materials used in the LPDC.

Impact category	Unit	Total	AlMg3	TiO2	Argon	Filters	Die coating (zircon)	Electricity
Climate change	kg CO2 eq	1,27E+01	1,03E+01	6,62E-02	1,01E+00	4,50E-05	2,91E-03	1,32E+00
Ozone depletion	kg CFC-11 eq	1,47E-06	1,18E-06	7,28E-09	1,25E-07	2,48E-12	1,53E-10	1,62E-07
Human toxicity, non-cancer effects	CTUh	5,96E-06	5,07E-06	2,77E-08	3,40E-07	1,03E-11	6,48E-10	5,24E-07
Human toxicity, cancer effects	CTUh	3,03E-06	2,81E-06	2,02E-08	8,56E-08	2,34E-12	1,79E-10	1,22E-07
Particulate matter	kg PM2.5 eq	1,46E-02	1,35E-02	8,68E-05	4,08E-04	2,92E-08	2,27E-06	5,76E-04
Ionizing radiation HH	kBq U235 eq	2,69E+00	1,42E+00	7,55E-03	5,49E-01	3,19E-06	2,27E-04	7,10E-01
Ionizing radiation E (interim)	CTUe	7,14E-06	3,86E-06	2,46E-08	1,42E-06	1,15E-11	8,39E-10	1,84E-06
Photochemical ozone formation	kg NMVOC eq	5,32E-02	4,76E-02	2,72E-04	2,27E-03	2,05E-07	1,30E-05	3,05E-03
Acidification	molc H+ eq	8,78E-02	7,34E-02	1,34E-03	5,52E-03	2,08E-07	2,09E-05	7,57E-03
Terrestrial eutrophication	molc N eq	1,53E-01	1,32E-01	7,93E-04	8,58E-03	4,07E-07	4,90E-05	1,15E-02
Freshwater eutrophication	kg P eq	7,58E-03	5,23E-03	2,79E-05	9,92E-04	1,32E-08	1,57E-06	1,32E-03
Marine eutrophication	kg N eq	1,56E-02	1,32E-02	8,71E-05	9,69E-04	4,48E-08	4,70E-06	1,28E-03
Freshwater ecotoxicity	CTUe	3,31E+02	2,68E+02	1,50E+00	1,38E+01	6,42E-04	2,29E-02	4,72E+01
Land use	kg C deficit	1,98E+01	1,73E+01	1,37E-01	7,93E-01	4,20E-05	1,08E-02	1,51E+00
Water resource depletion	m3 water eq	6,04E-02	3,11E-02	5,17E-04	1,56E-02	8,23E-08	3,04E-06	1,32E-02
Mineral, fossil & ren resource depletion	kg Sb eq	4,34E-03	4,26E-03	4,36E-05	8,96E-06	9,02E-10	7,77E-06	1,85E-05

Table S6. Characterization of environmental impacts from processes used in the LPDC.

Impact category	Unit	Total	Process 1	Process 2	Process 3	Process 4	Process 5	Process 6
Climate change	**kg CO2 eq**	1,27E+01	1,14E+01	1,01E+00	2,52E-03	2,33E-01	6,29E-05	3,71E-02
Ozone depletion	**kg CFC-11 eq**	1,47E-06	1,31E-06	1,26E-07	3,10E-10	2,86E-08	7,75E-12	4,54E-09
Human toxicity, non-cancer effects	**CTUh**	5,96E-06	5,51E-06	3,41E-07	9,99E-10	9,22E-08	2,50E-11	1,47E-08
Human toxicity, cancer effects	**CTUh**	3,03E-06	2,92E-06	8,57E-08	2,33E-10	2,15E-08	5,81E-12	3,41E-09
Particulate matter	**kg PM2.5 eq**	1,46E-02	1,41E-02	4,09E-04	1,10E-06	1,03E-04	2,75E-08	1,63E-05
Ionizing radiation HH	**kBq U235 eq**	2,69E+00	1,99E+00	5,50E-01	1,35E-03	1,24E-01	3,39E-05	1,98E-02
Ionizing radiation E (interim)	**CTUe**	7,14E-06	5,34E-06	1,43E-06	3,50E-09	3,22E-07	8,76E-11	5,12E-08
Photochemical ozone formation	**kg NMVOC eq**	5,32E-02	5,03E-02	2,28E-03	5,81E-06	5,45E-04	1,45E-07	8,68E-05
Acidification	**molc H+ eq**	8,78E-02	8,07E-02	5,52E-03	1,44E-05	1,34E-03	3,61E-07	2,13E-04
Terrestrial eutrophication	**molc N eq**	1,53E-01	1,42E-01	8,60E-03	2,19E-05	2,05E-03	5,47E-07	3,23E-04
Freshwater eutrophication	**kg P eq**	7,58E-03	6,31E-03	9,94E-04	2,52E-06	2,33E-04	6,31E-08	3,69E-05
Marine eutrophication	**kg N eq**	1,56E-02	1,43E-02	9,71E-04	2,45E-06	2,29E-04	6,13E-08	3,62E-05
Freshwater ecotoxicity	**CTUe**	3,31E+02	3,07E+02	1,39E+01	9,00E-02	8,28E+00	2,25E-03	1,32E+00
Land use	**kg C deficit**	1,98E+01	1,86E+01	7,95E-01	2,87E-03	2,74E-01	7,18E-05	4,23E-02
Water resource depletion	**m3 water eq**	6,04E-02	4,21E-02	1,56E-02	2,52E-05	2,31E-03	6,29E-07	3,68E-04
Mineral, fossil & ren resource depletion	**kg Sb eq**	4,34E-03	4,32E-03	8,98E-06	3,52E-08	1,10E-05	8,81E-10	5,23E-07

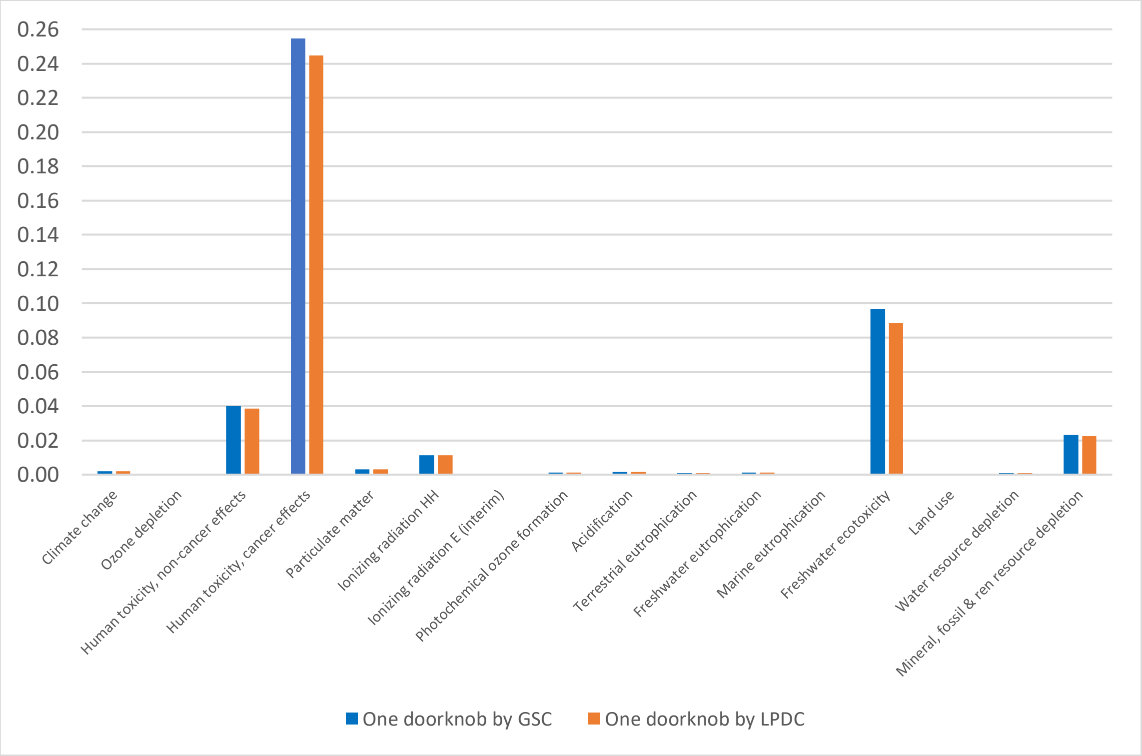

Figure S1. Normalization factor comparative between GSC and LPDC.

Table S7. Weighting score results comparative between GSC and LPDC.

Impact category	Unit	One doorknob by GSC	One doorknob by LPDC
Total	**mPt**	**29,183871**	**27,749460**
Climate change	**mPt**	0,123512	0,119606
Ozone depletion	**mPt**	0,008284	0,008042
Human toxicity, non-cancer effects	**mPt**	2,677429	2,564891
Human toxicity, cancer effects	**mPt**	16,972151	16,312598
Particulate matter	**mPt**	0,200293	0,192164
Ionizing radiation HH	**mPt**	0,751736	0,743224
Ionizing radiation E (interim)	**mPt**	0,000000	0,000000
Photochemical ozone formation	**mPt**	0,081335	0,078290
Acidification	**mPt**	0,108373	0,104355
Terrestrial eutrophication	**mPt**	0,064647	0,062297
Freshwater eutrophication	**mPt**	0,079341	0,077247
Marine eutrophication	**mPt**	0,035363	0,034123
Freshwater ecotoxicity	**mPt**	6,466214	5,893907
Land use	**mPt**	0,000270	0,000253
Water resource depletion	**mPt**	0,053925	0,058447
Mineral, fossil & ren resource depletion	**mPt**	1,560997	1,500014

Table S8. Weighting score results for the reusing scenarios.

Impact category	Unit	One doorknob by GSC (with alloy reusing scenario)	One doorknob by LPDC (with alloy reusing scenario)
Total	**mPt**	**4,785076**	**4,379293**
Climate change	**mPt**	0,027054	0,027215
Ozone depletion	**mPt**	0,001892	0,001919
Human toxicity, non-cancer effects	**mPt**	0,510052	0,488888
Human toxicity, cancer effects	**mPt**	1,953715	1,927323
Particulate matter	**mPt**	0,023187	0,022525
Ionizing radiation HH	**mPt**	0,361543	0,369482
Ionizing radiation E (interim)	**mPt**	0,000000	0,000000
Photochemical ozone formation	**mPt**	0,011717	0,011607
Acidification	**mPt**	0,020624	0,020306
Terrestrial eutrophication	**mPt**	0,011154	0,011059
Freshwater eutrophication	**mPt**	0,026345	0,026485
Marine eutrophication	**mPt**	0,006534	0,006510
Freshwater ecotoxicity	**mPt**	1,716984	1,344901
Land use	**mPt**	0,000049	0,000042
Water resource depletion	**mPt**	0,023726	0,029521
Mineral, fossil & ren resource depletion	**mPt**	0,090500	0,091512

Table S9. Cost analysis for GSC and LPDC.

Green Sand Casting				
Activity	Quantity	Unit cost	Furnace cost	Doorknob cost
Process 1 – Induction furnace				
Energy (kWh)	180	0,0822 €	14,7960 €	0,3699 €
Labour force (€/h)	4	16,3636 €	65,4545 €	1,6364 €
Materials (kg)	50	161€	227,5 €	5,6875 €
AlMg3	49,5	3 €	148,5 €	3,7125 €
TiO2	0,5	158€	79 €	1,9750 €
Machinery	1	8.257€	2,2936 €	0,0573 €
Total cost			310,0442 €	7,7511 €
Process 2 – Ultrasonic equipment				
Machinery	1	5.000 €	1,3889 €	0,0347 €
Energy (kWh)	0,75	0,0822 €	0,0617 €	0,0015 €
Labour force (€/h)		16,3636 €	0 €	0 €
Total cost			1,4505 €	0,0363 €
Process 3 – Density control				
Machinery	0	0 €	0 €	0 €
Energy(kWh)	0,02	0,0822 €	0,0016 €	0,0000 €
Labour force (€/h)		16,3636 €	0 €	0 €
Total cost			0,0016 €	0,0000 €
Process 4 – Fume capting				
Machinery	1	1.520,12 €	0,0317 €	0,0008 €
Filters	1	96,2390 €	0,0200 €	0,0005 €
Energy (kWh)	10,5	0,0822 €	0,8631 €	0,0216 €
Total cost			0,9148 €	0,0229 €
Process 5 & 8 – Crane hoist				
Machinery	1	860,2 €	0,2389 €	0,0060 €
Labour force (€/h)	0,0167	16,3636 €	0,2727 €	0,0068 €
Energy (kWh)	1,3333	0,0822 €	0,1096 €	0,0027 €
Total cost			0,6213 €	0,0155 €
Process 6 & 7 – Preparation and mixing of sand				
Material (kg)	101,67	11,1299 €	0,0036 €	0,0001 €
Sand (SiO2)	90	0,1 €	0,0900 €	0,0023 €
Bentonite	8,38	3 €	0,2514 €	0,0063 €
Lustrous carbon	3,14	0,28 €	0,0088 €	0,0002 €
SO2	0,05	0,4984 €	0,0002 €	0,0000 €
H3BO3	0,1	7,2515 €	0,0073 €	0,0002 €
Water (l)	3,14	0,0019 €	0,0001 €	0,0000 €
Energy (kWh)	15	0,0822 €	1,2330 €	0,0308 €
Machinery	1	40.000, €	5,5556 €	0,1389 €
Labour force (€/h)	1	32,7273 €	32,7273 €	0,8182 €
Total cost			39,5158 €	0,9880 €
Process 9 – Pressure mold manufacture				
Mold	1	4.000 €	40 €	1 €
Labour force (€/h)	1	32,7273 €	32,7273 €	0,8182 €
Total cost			72,7273 €	1,8182 €
Process 10 – Blowing leftover sand				
Machinery			0 €	0 €
Energy (kWh)	1,5	0,0822 €	0,1233 €	0,0031 €
Labour force (€/h)	0,0833	16,3636 €	1,3636 €	0,0341 €
Total cost			1,4869 €	0,0372 €
Process 11 – Mold & Unmoulding				
Machinery			0 €	0 €
Energy (kWh)		0,0822 €	0 €	0 €
Labour force (€/h)	0,5	32,7273 €	16,3636 €	0,4091 €
Total cost			16,3636 €	0,4091 €
TOTAL			441,6392 €	11,0782 €
Indirect costs			1,5838 €	0,0396 €
TOTAL COST			**443,2230 €**	**11,1178 €**

Low Pressure Die Casting				
Activity	Quantity	Unit cost	Furnace cost	Doorknob cost
Process 1 – Induction furnace				
Energy (kWh)	300	0,0822 €	24,6600 €	0,1973 €
Machinery	1	1826,33 €	0,5073 €	0,0041 €
Labour force (€/h)	6	32,7273 €	196,3636 €	1,5709 €
Materials	150	161 €	682,5 €	5,4600 €
AlMg3	148,5	3 €	445,5 €	3,5640 €
TiO2	1,5	158 €	237 €	1,8960 €
Total cost			904,0310 €	7,2322 €
Process 2 – Rotary degassing unit				
Machinery	1	22839,385 €	6,3443 €	0,0508 €
Argon (l)	60	2 €	120 €	0,9600 €
Energy (kWh)	0,42	0,0822 €	0,0345 €	0,0003 €
Labour force (€/h)	0,5	32,7273 €	16,3636 €	0,1309 €
Total cost			142,7424 €	1,1419 €
Process 3 – Ultrasonic treatment				
Machinery	1	5000 €	1,3889 €	0,0111 €
Energy (kWh)	0,72	0,0822 €	0,0592 €	0,0005 €
Labour force (€/h)	0,75	32,7273 €	24,5455 €	0,1964 €
Total cost			24,6046 €	0,1968 €
Process 4 – Casting process LPDC				
Machinery	1	83052,3 €	23,0701 €	0,1846 €
Mold	1	25000 €	13,8889 €	0,1111 €
Labour force (€/h)	0,6667	32,7273 €	21,8182 €	0,1745 €
Energy (kWh)	66	0,0822 €	5,4252 €	0,0434 €
Total cost			64,2024 €	0,5136 €
Process 5 – Reduced Pressure test				
Machinery			0 €	0 €
Labour force (€/h)	0,5	32,7273 €	16,3636 €	0,1309 €
Energy (kWh)	0,0180	0,0822 €	0,0015 €	0,0000 €
Total cost			16,3651 €	0,1309 €
Process 6 – Fume capting				
Filters	1	96,2390 €	0,0134 €	0,0001 €
Machinery	1	1520,12 €	0,0211 €	0,0002 €
Energy (kWh)	10,5	0,0822 €	0,8631 €	0,0069 €
Total cost			0,8631 €	0,0071 €
TOTAL			1152,8086 €	9,2226 €
Indirect costs			0,5491 €	0,0044 €
TOTAL COSTS			**1153,3577 €**	**9,2270 €**

4. Life Cycle Assessment for different metal powder production technologies.

Environmental awareness and the necessary reduction in costs in industrial processes has facilitated the development of novel techniques such as Additive Manufacturing, decreasing the amount of raw materials and energy needed. The longing for improved materials with different and enhanced properties has resulted in research efforts in the Metal Matrix Composites field. These two novelties combined minimise environmental impacts and costs without compromising technical properties. Two technologies can feed Additive Manufacturing techniques with metallic powder: Gas Atomization and High Energy Ball Milling. This study provides a comparative Life Cycle Assessment of these technologies to produce one kilogram of metallic powder for the Directed Energy Deposition technique: a Ti6Al4V alloy, and a Ti6Al4V-TiC Metal–Matrix Composite, respectively. The LCA methodology is according to ISO 14040:2006, and large amounts of information on the use of raw materials, energy consumption, and environmental impacts is provided. Different impact categories following the Environmental Footprint methodology were analysed, showing a big difference between both technologies, with an 87.8% reduction of kg CO2 eq. emitted by High Energy Ball Milling in comparison with Gas Atomization. In addition, an economic analysis was performed, addressing the viability perspective and decision making and showing a 17.2% cost reduction in the conventional process.

This work has been published in Sustainability, Volume 15, under the following reference: *Santiago-Herrera, M. et al., 2023. Comparative Life Cycle Assessment* *and Cost Analysis of the Production of Ti6Al4V-TiC Metal–Matrix Composite Powder by High-Energy Ball Milling and Ti6Al4V Powder by Gas Atomization. Sustainability, 15 (2023), 6649. 10.3390/su15086649.*

4.1. Introduction.

Current regulation aiming for the reduction of environmental impacts is increasing. The Paris Agreement (United Nations, 2016) was the first international agreement to fight against climate change with a reduction of emissions target at 55% below 1990 levels, and the European Union (EU) is addressing it through policy initiatives under the European Green Deal (European Commission, 2019), seeking climate neutrality in the EU by 2050. Additionally, according to the Intergovernmental Panel on Climate Change, regulation on Greenhouse Gas emissions will be stricter and will come in the form of both penalties and incentives (IPCC, 2021), highlighting the need for an environmentally friendly industry approach. This reduction can be reached by reducing the use of resources in manufacturing, but most importantly on the production of primary material process, where the greatest amount of energy is consumed (Canakci & Varol, 2014). In recent decades, due to the increasing complexity of industrial components, industries have started to use metal powders (Kassym & Perveen, 2020), leading to the implementation of Additive Manufacturing (AM) techniques, which are more convenient for this purpose. Therefore, the use of powder metallurgy is progressing as an opposition to subtractive manufacturing, allowing more design possibilities and reducing the use of feedstock and energy at the same time (Duda & Raghavan, 2016).

AM is defined as a “process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies” by ASTM and ISO standards (ISO/ASTM 52900:2021). It can provide many significant advantages over traditional processes such as: decreased production time; a reduction of operator intervention; the non-requirement of multiple tools; ability to design and manufacture complex geometries; improvement of cost-competitiveness using expensive materials; negligible production of scraps and waste by using only the exact amount of material; non-necessity of adjuvants, coolants and lubricants; and transformation of the supply chain, enabling local and proximity production (Srivastava & Rathee, 2022; Ahn, 2021; Blakey-Milner et al., 2021; Torres-Carrillo et al., 2020; Fredriksson, 2019). All these advantages make AM a promising technology for Industry 4.0 and the transition to a Circular Economy by reducing the use of resources and extending products’ service lives, for instance by increasing the capability to repair specific and complex components (Gouveia et al., 2022). The interest from the industry in adopting AM technologies in their production processes is reflected in the markets. The global metal AM market is expected to grow around 24% annually until 2027 (Global Industry Analysts Inc, 2021). This means that the adoption of AM at a large scale will develop economies of scale, reducing costs for raw material and machinery investments and allowing firms to create cost-effective business models that can optimise the use of resources in production processes considering the whole supply chain, compared with conventional manufacturing methods (Thomas, 2016).

This study compares the production of commercial Ti6Al4V titanium alloy powders by Gas Atomization, which is the conventional and more common process to obtain feedstock for Additive Manufacturing, with the production of a titanium metal matrix composite formed by Ti6Al4V (whose titanium comes in the form of irregular powder by Kroll process) and TiC nanoparticles under a High Energy Ball Milling process. A Life Cycle Assessment (LCA) and a cost analysis has been carried out, as the demand for this integration is increasing (França et al., 2021). These two slightly different powders can be compared under the same LCA framework without compromising the consistency of the study because they have an identical function. Both powders can be used and are compared specifically for the Directed Energy Deposition technique, which is an AM process where the powder material is simultaneously fused by an energy source depositing material in a continuous way, forming a melt pool layer by layer (Svetlizky et al., 2021). To our knowledge, this type of evaluation on these technologies has not been performed to date in this research field. Thus, the present paper provides new primary data from the evaluated process and sets a basis for further evaluation of the technology.

Regarding the relevance of the manufacturing sector, a 7% annual expansion from 2020 to 2027 is expected for the powder metal subsector in particular (Grand View Research, 2020), as titanium was the material with the highest revenue share in the AM metal market in 2020 (Grand View Research, 2021); thus, it is important to assess the environmental impacts of these manufacturing techniques, which can be performed applying the LCA standardised methodology, to create awareness and support decision-making towards a more sustainable and eco-friendly industry.

4.2. Literature review.

In order to provide more insights about the technologies evaluated and the cases under study, and to give proper reasoning for the further modelling steps, a broad review was carried out including the process description of both the methods and materials under scope.

Currently, Gas Atomization (GA) is the leading processing method to produce metal powders for AM [20]. During this process, liquid metal melted in a furnace is sprayed into droplets by a pulverisation of high-pressurised gas, which fall into a cooling chamber under inert gas protection to solidify, form, and obtain metal powder particles with fine sizes (<100 μm), high sphericity, and flowability (Kim et al., 2021; Perminov et al., 2021; Sun et al., 2017). In the route of nanostructured materials production, a better alternative to the aforementioned method is High Energy Ball Milling (HEBM), a simple and powerful process to produce them (Kieback et al., 1993). This technique is greatly used for the production of nanocomposite powders, based on different processes taking place simultaneously, such as: cold welding, which increases the average particle size of the composite; fracturing, which causes fragmentation of the particles; and the re-welding of ceramic particles and metallic powders. All of this takes place in a highly activated milling media, where the impact of one ball with another and with the container wall in a repetitive way uniformly distributes the particles to achieve fine grained nanostructures (Ye et al., 2006; Ozdemir et al., 2008; Bathula et al., 2012; Singh et al., 2019). This powder metallurgy technique can be used to produce matrix whole range reinforcement compositions, known as Metal Matrix Composites (MMCs), which are materials made up from two or more constituents, where normally one is a metal, called the matrix, and the other one a ceramic, which is the reinforcement material, whose combination produces a material with different and superior characteristics to the component constituents (Ramanathan et al., 2019; Jamwal et al., 2020; Jayamani et al., 2021). This process allows the creation of mechanically strong interfaces between the nanoparticles and the matrix, avoiding miscibility inconveniences (Cabeza et al., 2017). Creating nanocomposite materials with a uniform reinforcement distribution is a difficult step, but the high collision rate and the bigger number of free surfaces produced under the HEBM process helps to achieve it (Manohar et al., 2021); this method is technically suitable for MMC powder production, in opposition to GA.

The production of nanostructured materials by HEBM, such as the MMCs, has received extraordinary attention over recent years, mainly because of their functional and structural characteristics, and most recently for their use in AM fabrication (Li et al., 2021). It has become an area of research given its easy application, which leads to the production of these advanced materials with enhanced physical and mechanical properties such as higher strength, stiffness, light weight, and wear resistance, whose potential applications generate a great interest in industry (Ozdemir et al., 2008). Habitually, these materials have been produced by casting techniques that obtain billet forms as a result, which have to be processed under subtractive methods, losing material and increasing the cost; thus, powder metallurgy methods offer advantages in this field (Behera et al., 2019). In the present, MMCs are the best alternative to the conventional materials (Hossain et al., 2020) and are preferred over the metals, non-metals, and alloys (Garg et al., 2019), replacing them in an exponential way in different industries (aerospace, automobile, defence, etc.) because of their superior mechanical properties and lesser cost to make them (G. Baskaran et al., 2015; A. Kumar et al., 2021). These materials play an important role in today's necessity of higher production and productivity in manufacturing, while having lower cost increases and reconciles these needs with environmental preservation by reducing the energy consumption, waste generation, and raw material consumption (Alves et al., 2014).

Regarding the material involved in this study, the increase in the demand of titanium and its alloys in new technologies (automotive, aerospace, biomedical…) has made the research in the development of new processes that consume less energy and require less material very relevant (Xia et al., 2019; Restrepo et al., 2020). Titanium and its alloys have exceptional properties such as low density, a low elastic modulus, high-specific strength, good formability, reasonable ductility, high fracture toughness, the ability to withstand high temperatures, biocompatibility, and good corrosion resistance (Restrepo et al., 2020). Specifically, titanium matrix composites have good performance in corrosion resistance, high specific strength, high specific modulus, and heat resistance (Yang et al., 2006). In particular, the Ti6Al4V alloy (Ti, 6 wt.% Al, 4 wt.% V), the focus of this study and which is the most widely used titanium alloy (Azevedo et al., 2003), has good characteristics such as a high strength to weight ratio, corrosion resistance, biocompatibility, and low thermal expansion (Gökelma et al., 2018). Additionally, the use of TiC ceramic particles as a reinforcement phase is interesting due to their high melting point, elastic modulus, high hardness, low density, high flexure strength, good thermal conductivity, high resistance to corrosion and oxidation, and high thermal shock resistance (Mhadhbi, 2020). These improved characteristics have been recently demonstrated by several different works, where the combination with ceramic particles increases the wear resistance, corrosion, and strength of the fabricated part (Anbarasan et al., 2022; Y. Li et al., 2022; Shang et al., 2022; N. Singh et al., 2021).

Previous studies also confirm the suitability of irregular and not spherical titanium feedstock powder for AM processing, using titanium sponge from conventional Kroll processes and starting from ilmenite ore mineral extraction converted to TiCl4, which is reduced by magnesium, obtaining a sponge that is sliced and crushed (Earlam, 2019); another option is hydrogenated-dehydrogenated (HDH) titanium, which can be produced by hydrogenation of nearly any source of titanium (Barbis et al., 2015). For instance, titanium sponge from the Kroll process was directly ball milled and then consolidated by Spark Plasma Sintering in a work by Zadra (2014). Arias-González et al. (2018) studied the deposition by Laser Cladding of irregularly shaped Ti grade four powder, demonstrating its viability. A comparative work, using the Directed Energy Deposition (DED) technique, was performed by Amado et al. (2019) between gas atomization Ti powders and sponge fines from the Kroll process, obtaining a harder printed layer from the sponge one at lower cost. In their work, Goso and Kale (2011) stated that the main source of titanium powder to be blended with other elements to produce alloys, such as Ti6Al4V, is the sponge product of the Kroll process; they also prepared a laboratory-scale approach to hydrogenate and mill these products, making them suitable for metallurgical compacts. Sponge elemental titanium powder and HDH elemental titanium powder were sintered under same conditions by Bolzoni et al. (2014) to compare their final mechanical characteristics. Dong et al. (2021) transformed non-spherical hydrogenated-dehydrogenated (HDH) titanium powder into spheres and printable forms using a ball milling method, grounded it until its morphology was near-spherical to further blend it with elemental powders of aluminium and vanadium, and developed low-cost HDH Ti-6Al-4V, which was later printed using a Laser-Based Powder Bed Fusion machine. Electron Beam Powder Bed Fusion was used by Narra et al. (2020) to successfully print parts from Ti6Al4V HDH powder compared with spherical atomized powder, obtaining similar qualities. In other work by X. Yang et al. (2020), irregular HDH titanium was modified in an HEBM to fabricate parts by Selective Laser Melting, reducing in this way the cost of using high-purity spherical powder, similar to the results achieved by Hou et al. (2019) manipulating HDH Ti by ball milling technology to produce printable Ti powders for the same AM technology. In addition, other kind of techniques, such as the disproportionation reaction in molten NaCl-KCl, have demonstrated the production of powders from titanium sponge (Lu et al., 2019).

The information retrieved from different sources shows the differences between both manufacturing techniques and the materials involved in the assessment. It also supports the utilisation of irregular powder in the HEBM process.

4.3. Materials and methods.

This study was conducted under the Environmental Life Cycle Assessment methodology, also known as simply Life Cycle Assessment (LCA), which is a management tool to evaluate the environmental performance of products, goods, and services (ISO, 2006b). The LCA methodology to be used is according to the ISO framework (ISO, 2006a) and refers to the recommendations and requirements given by the European ILCD guidelines (European Commission, 2010). In addition, the instructions included in Life Cycle Assessment: Theory and

Practice (Hauschild et al., 2017) were used as a background to complete the study and methodology explanation.

4.3.1. Case study.

The present study was carried out with the aim of knowing and comparing the environmental impact of two different processes, both capable of producing useful material for additive manufacturing techniques: (i) an MMC powder formed by Ti6Al4V and TiC nanoparticles with an HEBM process, and (ii) a Ti6Al4V alloy powder produced by GA was carried out under an LCA framework. These processes were developed by MBN Nanomateralia S.p.A within the framework of the European LightMe project (GA. 814552). The powder production started with the selection of commercially available raw materials at an industrial scale (Ti6Al4V and TiC) which were, in the first case, mechanically alloyed via High Energy Ball Milling under inert atmosphere (to prevent oxygen and nitrogen uptake). The powder output was then sieved, and coarser particle size fraction was re-processed to increase the overall process yield. Finally, in the range of 45–106 µm Ti6Al4V-TiC, powder suitable for AM was obtained. In the second case process, a high-velocity gas, argon in this case, disrupted the melting metal, producing spherical-shaped particles in the range of 50–150 µm, already proven used in AM.

Scanning Electron Microscope (SEM) images of powder morphology for both produced samples are shown in Figure 1, highlighting the differences between the products obtained through HEBM and GA. Despite the visible morphological differences, both products are suitable for use in the Directed Energy Deposition technique.

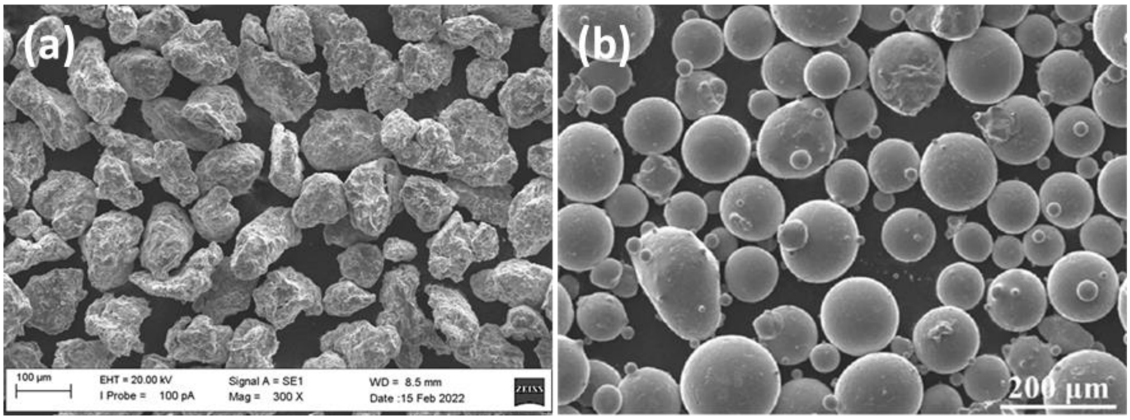

Figure 9. SEM image of powder morphology of (a) Ti6Al4V-3.8 wt.% TiC produced by HEBM and (b) Ti6Al4V produced by GA, extracted from Chen et al. (2018).

4.3.2. Goal and scope.

As stated in the Introduction, the main aim of this Life Cycle Assessment is to inform about the environmental performance, developing a comprehensive analysis of the production process of metal powder appropriate for Additive Manufacturing processes. This is conducted using a Metal Matrix Composite material formed by a titanium alloy (Ti6Al4V) reinforced with TiC nanoparticles in a High Energy Ball Milling process, and comparing its performance with the production of Ti6Al4V powder under the conventional Gas Atomization process. Thus, environmental arguments for the selection between the different manufacturing technologies are provided. Aside from this, a cost analysis with the same aim and scope is performed in order to contribute to a balanced analysis between the environmental and economic impacts. In addition, the study intends to provide life cycle inventory datasets that can contribute to enhance the state of-the-art knowledge of these manufacturing techniques.

These two different manufacturing techniques are modelled consistently in terms of both methodological choices and selection of data to obtain a fair representation of the two systems, and comply with the ISO 14044:2006 requirements. The functional unit is the production of one kilogram of metallic powder suitable to be used in Additive Manufacturing processes, specifically for Direct Energy Deposition techniques. This is an appropriate unit to assess both systems considering all the current constraints and possible further study steps, and the fact that they share the same final purpose, despite their different composition and production methods. This study is framed in a cradle-to-gate system boundary, as downstream data are not yet available, where all the inputs (raw materials and energy) and the outputs (product, emissions, and wastes) associated with the core process are considered. Upstream activities, such as the extraction of materials and their transportation to the factory, are considered based on the database used, which collects and integrates data from all the production stages of each input in an average approach. Downstream activities such as distribution, final use, and disposal, were not considered at this stage of the study due to nuances to obtain accurate data and properly assess these outbound steps.

4.3.3. Life Cycle Inventory.

For the inventory elaboration, the main data were provided by MBN Nanomateralia S.p.A, who are the MMC producers in their HEBM line. They also provided the data for the GA based on their previous knowledge and projects developed. All these data are backed by the progress of the LightMe project funded under the Horizon 2020 research program.

In the information about HEBM, a scaled-up production was contemplated, considering the reprocessing of un-used powders by sieving and reintroducing them in the process and argon recirculation. For the GA case, the recirculation rate was extracted from Wilson et al. (2013), who conducted an LCA on GA for nickel, expecting a 98% argon use reduction in an augmented approach, which is also in line with industrial purification systems.

All these data were processed, together with information extracted from the literature and from LCA databases, using ecoinvent v3.8 (Wernet et al., 2016), which allows the use of georeferenced data and different allocation approaches. In particular, the APOS (Allocation at the Point Of Substitution) system model was adopted, which follows the attributional approach in which burdens are attributed proportionally to specific processes. Moreover, as some processes and materials were not available in the existing LCA database, specific models were created ad hoc for this purpose based on scientific documentation, which will be disclosed later on.

Table 5 presents all the data specifications based on the production of one kilogram of powder, showing the raw materials, energy, and other items necessaries for the entire definition of the HEBM and GA processes, as provided by the producer.

Table 5. Inventory data for HEBM (High Energy Ball Milling) and GA (Gas Atomization) processes.

Products	**HEBM (Ti-6Al-4V - 3.8 wt% TiC)**	**GA (Ti-6Al-4V Powder)**
Alloy quantity (kg/kg material produced)	1.13	1.3
NPs quantity (kg/kg material produced)	0.038	-
Energy consumption (kWh/kg material produced)	4.5	55
Argon (L/kg material produced)	0.4	200

Assumptions and Limitations

As was mentioned before, some of the processes and materials to be introduced in the model were not found in the ecoinvent v3.8 database, so it was necessary to create them for this study purpose. This is the case of the titanium alloy

Ti6Al4V, which was not part of the current database. In order to fit the model with the European context, the energy expenditure production and average transport distance for the AlMg3 alloy production, which is also modelled for the same geography area, was selected. To include in the assessment the different components of the alloy, several sets of proportions were found (Baccar et al., 2013; Saboori et al., 2018; Dong et al., 2021) to generate an average quantity of each of them, except for Vanadium, which was not available in the databases and did not have enough literature available to be modelled ad hoc for this case study. To overcome this, the Vanadium share in the alloy (4% weight) was substituted, adding it to the Titanium amount. In this way, it is possible to model the alloy and later obtain its environmental impacts. This information can be seen in the Supplementary Material, Table S1. In the case of the TiC, there were no data about its production process in the ecoinvent databases. However, the production of SiC and B4C was available, which are developed under similar processes, as is shown in the literature review performed in Table 6. According to this, the production process of TiC was modelled based on the SiC, because they have the same stochiometric reaction, changing the SiO_2 feedstock for TiO_2 and including the same transportation average based on an equal European context. From the B4C, only the type of chemical factory dataset was extracted, closer than a typical silicone factory used for the SiC case. The different datasets used can be found in Supplementary Material, Table S2.

Table 6. Overview of the literature review about TiC, SiC, and B4C production.

Author	Title	Main Findings
Guichelaar, 1997	Acheson Process. Carbide, Nitride and Boride Materials Synthesis and Processing	SiC production by Acheson method, pure silica (SiO_2) or quartz sand, and petroleum coke are used; the reaction that takes place has a 1:3 ratio.

Kumar and Gupta, 2002	Study of formation of silicon carbide in the Acheson process	Coke and silica sand are introduced into the Acheson furnace, highly energetic process over 6–12 kWh/kg SiC. After heating and subsequent cooling, it is taken to grinding and classification.
Chen et al., 2004	Synthesis and characterization of boron carbide nanoparticles	B4C nanoparticles were made via a reaction of boron, obtained from thermal decomposition of magnesium diboride, with multiwall carbon nano tubes at 1150 °C.
Woo et al., 2007	Formation of TiC particle during carbothermal reduction of TiO_2	The starting point is titanium dioxide TiO_2 and carbon resin (1:3 ratio), then put in a graphite furnace at 1500 °C, obtaining the product.
Nuilek et al., 2008	Production of titanium carbide from ilmenite	Ilmenite and carbon black are ground for 2 h at 250 rpm, in a ratio of 1:4, respectively, heated to a max. Tof 1500 °C maintained for 1 h.
Suri et al., 2013	Synthesis and consolidation of boron carbide: a review	B_2O_3 or H_3BO_3 with a carbon source in the furnace above 1400 °C for reduction, where the production of B4C will take place. The resulting powder is leached in acid to remove impurities.
Sen et al., 2011	Preparation of TiC powders by carbothermal reduction method in vacuum	Carbothermal reduction starting from TiO_2 takes place at a temperature of 1550 °C for 4 h.
Sonber et al., 2013	Synthesis, densification and characterization of Boron Carbide	B4C is produced commercially by carbothermal reduction in an electric arc furnace, reducing B_2O_3 with CO.
Kakiage et al., 2016	Low-temperature carbothermal nitridation of boron oxide induced by networked carbon structure	B4C powders are formed by carbothermal reduction with boron oxide through the reaction of $2B_2O_3 + 7C \rightarrow B4C + 6CO$.
Kukushkin, 2021	Special Issue: Silicon Carbide: From Fundamentals to Applications	Silicon carbide is composed of silicon and carbon, manufactured by a patented method called the Acheson method.

4.3.4. Impact assessment.

This phase allowed us to transform the Life Cycle Inventory data, collected as described in the previous section, into quantifiable environmental impacts. A specific software tool was used to create the models for the impact assessment calculation: SimaPro® 9.3 by Pre' Consultants, one of the most predominant LCA software. The impact assessment method used in this study was the EF method of the Environmental Footprint (EF) initiative, launched by the European Commission in 2013, in constant updating and transitioning phases. It was designed to support the use of Product Environmental Footprint Category Rules (PEFCR) and Organisation Environmental Footprint Sector Rules (OEFSR), and with the aim of creating a harmonised EU methodology with relevant environmental performance criteria using a life cycle approach (European Commission, 2013). This method provides information on 16 midpoint impact categories, extracted from Fazio et al. (2018): climate change (kg CO_2 eq.); ozone depletion (kg CFC11 eq.); ionising radiation (kBq U-235 eq.); photochemical ozone formation (kg NMVOC eq.); particulate matter (disease incidence); human toxicity, non-cancer (CTUh); human toxicity, cancer (CTUh); acidification mol (H+ eq.); eutrophication, freshwater (kg P eq.); eutrophication, marine (kg N eq.); eutrophication, terrestrial (mol N eq.); ecotoxicity, freshwater (CTUe); land use (Pt); water use (m3 deprived); resource use, fossils (MJ); resource use, minerals and metals (kg Sb eq.).

In this study, a normalisation factor was included, which according to ISO 14044:2006 is an optional step, to offer a common unit scale, providing a comparable set of results and solving in this way the incompatibility of different units by expressing the total impact occurring in a reference region for a certain impact category within a reference year. The normalisation factors in this assessment were based on Crenna et al. (2019). With this, the more significant impact categories for the product system under investigation arise. These are dimensionless results, meaning that, for instance, a global warming potential of 0.5 for a product or system means that it is responsible for half of the GWP emitted by an average person per year in that particular reference region. According to the ISO standard, weighting it is also an optional step, but it is included in the study because it can help in decision making, ensuring the focus is on the important aspects, and to add up the results, obtaining a single score that can serve as a comparison between technologies and with the cost analysis. This step aggregates in averages, three weighting sets: panel-based approach—general public survey; panel-based approach—LCA experts' survey; and evidence- and judgement-based approach, according to Sala et al. (2018). These sets are later multiplied by the normalisation factor of each category previously obtained, resulting in a score value measured in mPts.

4.3.5. Cost analysis.

When performing the LCA to identify the environmental impacts and study the different alternatives, it is also crucial to assess the economic impacts that the innovation can suppose. It may happen that changes are made to production processes to improve their environmental impacts, but the cost of implementing the innovation makes the business model unprofitable.

In this case, HEBM and GA processes have been assessed to calculate the cost of producing one kilogram of metallic powder suitable to be used in Additive Manufacturing processes, so the same functional unit as the one used for the LCA was considered. For this calculation, different activities incurred in the production processes were evaluated, obtaining economic information to facilitate the identification of cost-drivers and to be combined with the environmental impacts in a single matrix.

The economic data were collected from the same provider, MBN Nanomaterialia S.p.A, for one kilogram of produced powder (same FU as for the environmental assessment) to facilitate the comparison, including the capital cost and the operational costs. No more detailed disclosure is shown, as some data could be sensitive for the production company. This data can be found in Table 7.

Table 7. Economic data for HEBM (High Energy Ball Milling) and GA (Gas Atomization) processes.

Products	**HEBM (Ti6Al4V—3.8 wt.% TiC)**	**GA (Ti6Al4V Atomized Powder)**
Alloy price (EUR/kg)	27	17
NPs Price (EUR/kg)	3.7	0
Overall plant cost (EUR/kg)	51	38
Manufacturing time (kg/h)	4	6
Electricity (EUR/kg)	2	11
Personnel (EUR/kg)	1.6	4
Argon cost (EUR) (3 EUR/m^3)	0.0012	0.6
Total cost per kg (EUR)	**85.3**	**70.6**

4.4. Results and discussion.

After the modelling process, the calculation output is a set of values for the characterisation factors, which are presented in Supplementary Material, Tables S3 and S4. Then, the software helps to calculate the normalisation factors, accessible in Tables S5 and S6, which are necessary to obtain the final weighting factors shown in a single score value (mPts), which can be seen in Figures 10 and 11. The detailed score for each technology, showing the impacts produced by the inputs involved, can be found in Supplementary Material, Tables S7 and S8.

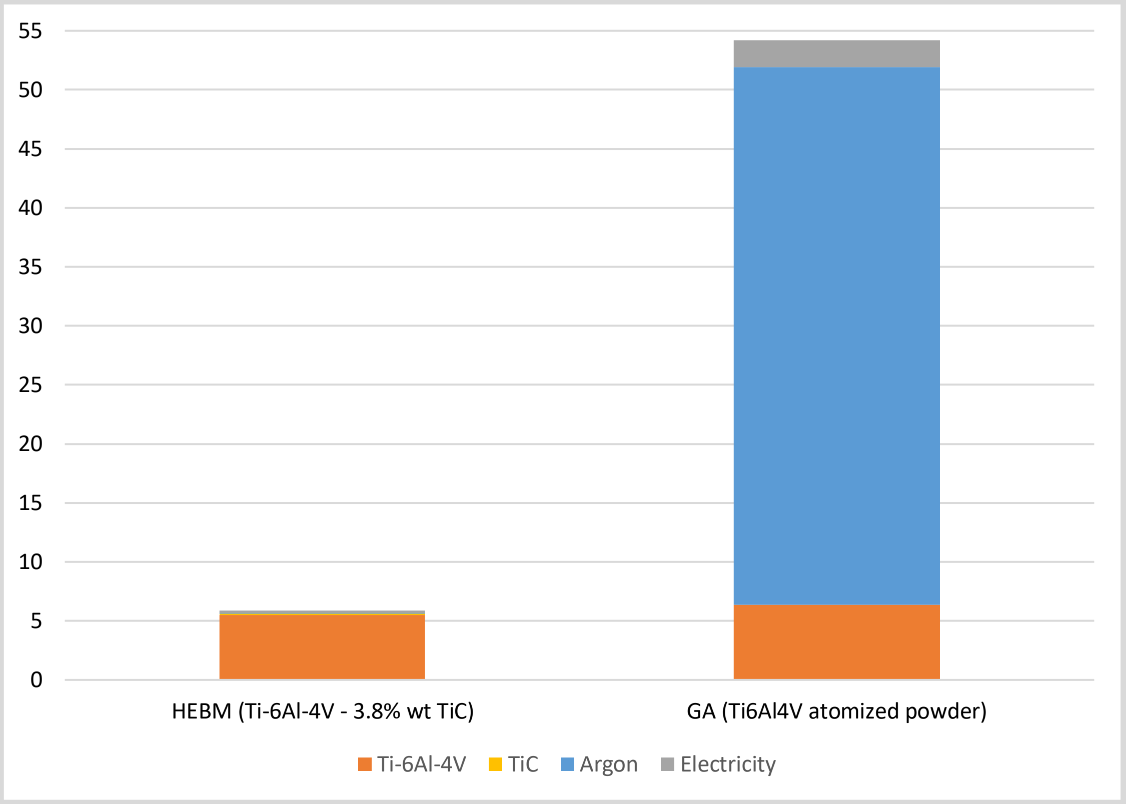

Figure 10. Weighting factors, by input material, for HEBM (High Energy Ball Milling) and GA (Gas Atomization) processes.

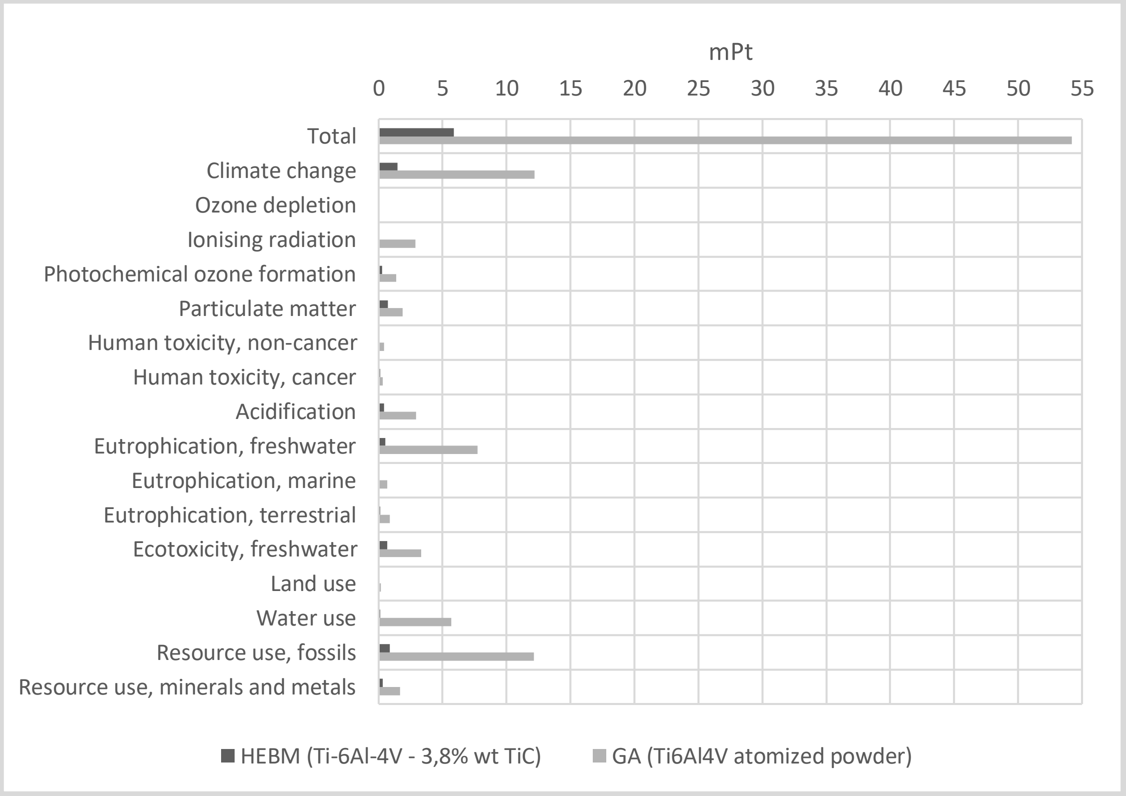

Figure 11. Weighting factors, by impact category, for HEBM (High Energy Ball Milling) and GA (Gas Atomization) processes.

The outcome of the previous analysis clearly shows that the production of one kg of metallic powder, useful for additive manufacturing techniques, is more environmentally harmful if is processed by GA rather than by HEBM. For instance, the single score of GA is more than 54 mPts, mainly due to argon use (84% of contribution), while almost 6 mPts are obtained for the HEBM technology, of which 94% of the impacts are due to Ti6Al4V use. Therefore, an 89% reduction is achieved by the implementation of the new process. Aside from argon, the environmental profile of the GA process is also influenced by the input of titanium alloy (12% on the single score). In relation with the energy expenditures, the GA process is almost 10 times more energetic than HEBM, as shown in the inventory table. However, its contribution to the total impact of each process is similar, explaining 4% and 3%, respectively. Regarding the HEBM process, the other process flows, TiC and argon, have a contribution lower than 2%.

Concerning the impact categories, the most important ones for the single score are Climate change and Use of fossil resources, for both technologies. In relation with the GA process, argon has the highest impact in the Water use category, with a 97% contribution. The Ti6Al4V alloy has its largest impact in Human toxicity, cancer, with more than 50% of the impacts. Electricity has a lower impact in all categories, representing a maximum of 5% in the Ionising radiation category. In the case of the HEBM, titanium alloy represents more than 98% both in the Particulate matter and Human toxicity, cancer categories. Electricity has is highest contribution in Ionising radiation with almost a 19%. The rest of the materials, argon and TiC, have a lower contribution, with their highest in the Water use category, representing 8% and 3%, respectively.

On the subject of the economic analysis, as can be observed on Table 7, the production of one kilogram of powder by the HEBM process has a higher economic impact than that of GA, with an almost 21% increment. This is due to the higher price of the raw material (alloy), the addition of the NPs, and the cost of the production plant.

The total weighting scores can be integrated with the cost analysis results, putting them together in a single matrix, and obtaining a valuable comparison between both technologies (Figure 12).

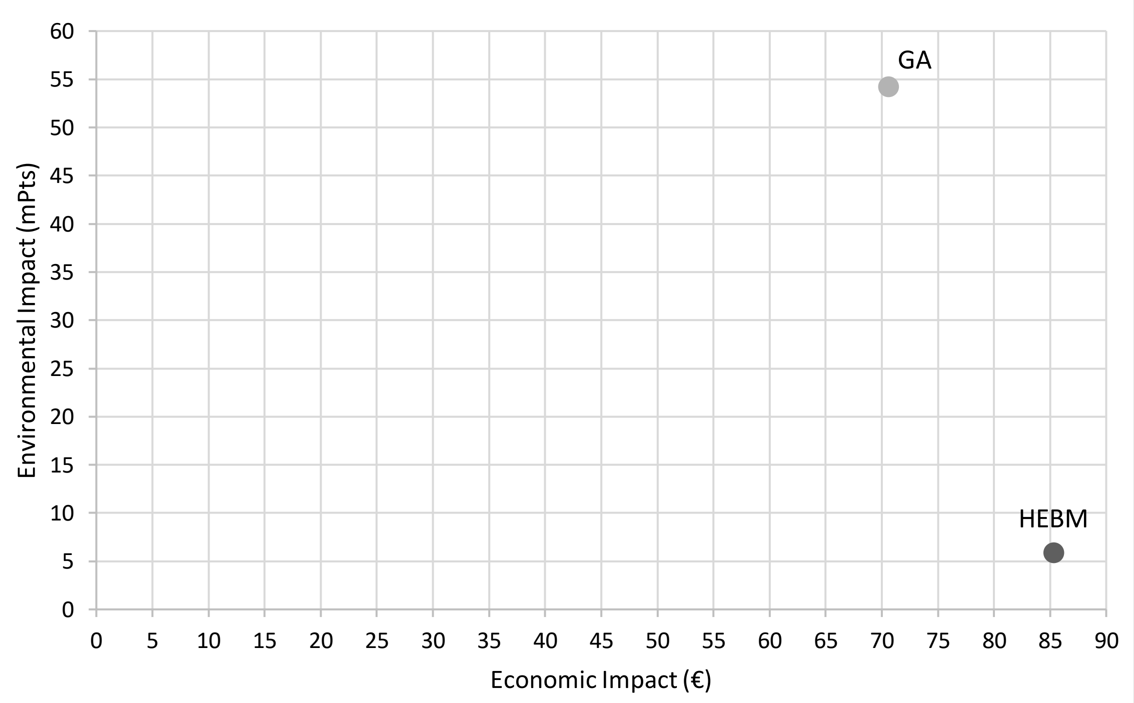

Figure 12. Comparison matrix chart of both technologies, HEBM (High Energy Ball Milling) and GA (Gas Atomization), with the environmental impact measured in mPts and the economic impact measured in EUR.

Other important data to consider are the energy consumption, with a total expenditure of 55 kWh in the GA and only 4.5 kWh used in the HEBM process, which represents a reduction of a 91.8%.

Certain constraints and limitations identified during the design process for the assessment concerning alloy and nanoparticle modelling increase the uncertainty of some of the aforementioned results, as described in the “Assumptions and limitations” subsection. In addition, the use of a global average transport approach for the materials and a standard European electricity mix could also have a slight implication on the final results. These limitations found during the modelling phase have low relevance in the final outcomes, but it was still necessary to address them to guide future replications of the study.

As mentioned in the Introduction, there is not vast research on this topic, using equal materials, to compare and discuss the obtained results of our study. However, a recent work by Dhiman et al. (2022) demonstrated a 68% lesser global warming potential from Ti6Al4V swarf processed to powder by ball milling, in comparison with its conventional GA counterpart. In this study, the swarf material used needed a pre-treatment involving different chemicals and energy flows, which could explain the impact reduction differences with the present study. This is aligned with the results here presented, also considering it uses different boundaries, impact methodology, and database.

4.5. Conclusions.

After the complete assessment, it is plainly evident that the production of one kilogram of metallic powder suitable for additive manufacturing techniques produces less environmental impact if it is manufactured under High Energy Ball Milling instead of that in the conventional Gas Atomization process, achieving a reduction in the order of 90%, measured under the weighting single score scale. This comparison has allowed us to find and better interpret the hotspots and cost-drivers of the assessment.

The main environmental issue comes from the intensive use of argon in the GA process, which leads to a higher damage score as the quantity used is 500 times bigger than that in the HEBM. For instance, the argon used in HEBM emits 0.77 kg CO_2 eq., while more than 384 kg results from GA. The use of this type of gas is necessary to achieve a good performance in the GA process, so a significative reduction in its quantity is not expected. Even in a hypothetical scenario with a smaller amount of argon needed, the higher energy expenditure of the conventional process would still generate more environmental impacts. Regarding the economic terms, which makes HEBM technology more expensive than its counterpart (about EUR 15 more per kg produced), it is the price of the alloy and the nanoparticle used, and specially the overall cost of the plant, which have not reached yet the same level of optimisation and maturity as those of the GA, so a possible cost reduction in the near future could be possible. In addition, the improvement in the HEBM powder properties can increase the value of the final product and make the innovation viable while reducing the environmental impacts. Moreover, the powder produced in the HEBM process has better characteristics than a regular alloy when applied to the manufacturing of any kind of component, making it lighter and more durable, which will also enhance the environmental performance during the use phase, having a longer life or, for instance, if it is applied in the transport sector, reducing fuel consumption by its lower weight. Further studies in this regard considering a specific application would be needed to verify to what extent the improved performance would compensate the costs. Additionally, to allow a more reliable comparability between systems, further research is needed to integrate other calculation methods and techniques, such as uncertainty and sensitivity analyses, to consolidate the LCA results. Additionally, in other fields of study, the mechanical behaviour and final functionality of the different powders should be compared with supplementary tests to assess different characteristics of the products, such as density.

This environmental evaluation, performed under the Life Cycle Assessment methodology, helps with the comparison of both technologies in order to evaluate their environmental performance. It has been demonstrated that the new process is not only capable of producing powder for additive manufacturing with improved properties from the industrial and consumer perspective, but it also can conduct it in a more environmentally friendly way. The integration of the cost analysis also supports the decision making, providing data of great interest for manufacturers.

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4.7. Supplementary information for Chapter 6.

Table S1. Average values and database sets for Ti-6Al-4V alloy.

Saboori et. al 2018 10.3791/56966	**Baccar et. al 2013** 10.1007/978-1-4614-4226-4_23	**Dong et. al 2021** 10.1016/j.addma.2020.101699	**Ti-6Al-4V average**		
			Element	**Percentage**	**ecoinvent database v3.8**
5,830	6	6	Al	5,9433	Aluminium, cast alloy {GLO}| market for | APOS, U
0,080	0,3	0,07	Fe	0,1500	Cast iron {GLO}| market for | APOS, U
0,017	0,08	0,053	C	0,0500	Carbon black {GLO}| market for | APOS, U
3,890	*4*	*4*	*V*	*3,9633*	*Not found in ecoinvent databases*
90,124	89,36	92	Ti	93,6512	Titanium, primary {GLO}| market for | APOS, U
0,001	0	0	S	0,0005	Sulfur {GLO}| market for | APOS, U
0,013	0,01	0	H	0,0077	Hydrogen, liquid {RER}| market for | APOS, U
0,022	0,05	0,009	N	0,0270	Nitrogen, liquid {GLO}| market for | APOS, U
0,023	0,2	0,288	O	0,1703	Oxygen, liquid {GLO}| market for | APOS, U

Table S2. Database sets for the inputs involved in the HEBM (High Energy Ball Milling) and GA (Gas Atomization) processes.

Products	**Alloy quantity (kg/kg material produced)**	**NPs quantity (kg/kg material produced)**	**Energy consumption (kWh/kg material produced)**	**Argon used (l/kg)**
Ti-6Al-4V – 3,8 wt% TiC	1,13	0,038	4,5	0,4
Reference (ecoinvent databases v3.8)	Titanium alloy, Ti-6Al-4V {GLO}| market for | APOS, U	Titanium carbide, TiC {GLO}| market for (based on SiC and B4C production and SiC market for) | APOS, U *	Electricity, medium voltage {Europe without Switzerland}| market group for | APOS, U	Argon, liquid {RER}| market for argon, liquid | APOS, U
Ti6Al4V powder	1,3	0	55	10.000
Reference (ecoinvent databases v3.8)	Titanium alloy, Ti-6Al-4V {GLO}| market for | APOS, U	-	Electricity, medium voltage {Europe without Switzerland}| market group for | APOS, U	Argon, liquid {RER}| market for argon, liquid | APOS, U

* TiO_2 (*Titanium dioxide {RER}*| *market for* | *APOS, U*) replaces SiO_2 (*Silica sand {GLO}*| *market for* | *APOS, U*), and *Chemical factory, organics {GLO}*| *market for* | *APOS, U* replaces *Silicone factory {RER}*| *construction* | *APOS, U*.

Table S3. Characterization factors for the HEBM (High Energy Ball Milling) process.

Impact category	**Unit**	**Total**	**Ti-6Al-4V**	**TiC**	**Argon**	**Electricity**
Climate change	kg CO2 eq	5,7E+01	5,4E+01	5,5E-01	7,7E-01	1,8E+00
Ozone depletion	kg CFC11 eq	7,0E-06	6,8E-06	7,4E-08	4,9E-08	1,1E-07
Ionising radiation	kBq U-235 eq	5,5E+00	3,9E+00	1,2E-01	4,5E-01	1,0E+00
Photochemical ozone formation	kg NMVOC eq	2,2E-01	2,1E-01	2,0E-03	1,8E-03	4,0E-03
Particulate matter	disease inc.	4,6E-06	4,5E-06	3,8E-08	1,4E-08	3,1E-08
Human toxicity, non-cancer	CTUh	8,8E-07	8,4E-07	1,2E-08	7,5E-09	1,7E-08
Human toxicity, cancer	CTUh	1,1E-07	1,1E-07	1,2E-09	2,4E-10	5,3E-10
Acidification	mol H+ eq	3,5E-01	3,3E-01	9,0E-03	4,2E-03	9,7E-03
Eutrophication, freshwater	kg P eq	3,1E-02	2,8E-02	2,5E-04	7,8E-04	1,8E-03
Eutrophication, marine	kg N eq	5,9E-02	5,6E-02	5,9E-04	7,4E-04	1,7E-03
Eutrophication, terrestrial	mol N eq	6,0E-01	5,8E-01	5,3E-03	6,4E-03	1,5E-02
Ecotoxicity, freshwater	CTUe	1,5E+03	1,4E+03	1,3E+01	1,1E+01	2,5E+01
Land use	Pt	2,7E+02	2,5E+02	3,8E+00	2,9E+00	6,7E+00
Water use	m3 depriv.	1,8E+01	1,5E+01	5,2E-01	1,5E+00	5,6E-01
Resource use, fossils	MJ	6,7E+02	6,1E+02	8,6E+00	1,7E+01	3,8E+01
Resource use, minerals and metals	kg Sb eq	2,5E-04	2,4E-04	2,9E-06	2,2E-06	4,6E-06

Table S4. Characterization factors for the GA (Gas Atomization) process.

Impact category	**Unit**	**Total**	**Ti-6Al-4V**	**Argon**	**Electricity**
Climate change	kg CO2 eq	4,7E+02	6,2E+01	3,8E+02	2,2E+01
Ozone depletion	kg CFC11 eq	3,4E-05	7,8E-06	2,5E-05	1,4E-06
Ionising radiation	kBq U-235 eq	2,4E+02	4,5E+00	2,2E+02	1,3E+01
Photochemical ozone formation	kg NMVOC eq	1,2E+00	2,4E-01	8,8E-01	4,9E-02
Particulate matter	disease inc.	1,2E-05	5,2E-06	6,8E-06	3,8E-07
Human toxicity, non-cancer	CTUh	4,9E-06	9,7E-07	3,8E-06	2,1E-07
Human toxicity, cancer	CTUh	2,5E-07	1,3E-07	1,2E-07	6,5E-09
Acidification	mol H+ eq	2,6E+00	3,8E-01	2,1E+00	1,2E-01
Eutrophication, freshwater	kg P eq	4,4E-01	3,2E-02	3,9E-01	2,2E-02
Eutrophication, marine	kg N eq	4,6E-01	6,4E-02	3,7E-01	2,1E-02
Eutrophication, terrestrial	mol N eq	4,0E+00	6,6E-01	3,2E+00	1,8E-01
Ecotoxicity, freshwater	CTUe	7,4E+03	1,6E+03	5,4E+03	3,0E+02
Land use	Pt	1,8E+03	2,9E+02	1,5E+03	8,1E+01
Water use	m3 depriv.	7,6E+02	1,7E+01	7,4E+02	6,9E+00
Resource use, fossils	MJ	9,5E+03	7,0E+02	8,3E+03	4,6E+02
Resource use, minerals and metals	kg Sb eq	1,4E-03	2,8E-04	1,1E-03	5,6E-05

Table S5. Normalization factors for HEBM (High Energy Ball Milling) process.

Impact category	Unit	Total	Ti-6Al-4V	TiC	Argon	Electricity
Climate change	-	7,055E-03	6,674E-03	6,847E-05	9,494E-05	2,182E-04
Ozone depletion	-	1,303E-04	1,259E-04	1,388E-06	9,138E-07	2,060E-06
Ionising radiation	-	1,306E-03	9,276E-04	2,835E-05	1,065E-04	2,433E-04
Photochemical ozone formation	-	5,420E-03	5,230E-03	4,872E-05	4,317E-05	9,867E-05
Particulate matter	-	7,777E-03	7,638E-03	6,449E-05	2,299E-05	5,167E-05
Human toxicity, non-cancer	-	3,830E-03	3,670E-03	5,253E-05	3,270E-05	7,439E-05
Human toxicity, cancer	-	6,686E-03	6,567E-03	7,364E-05	1,410E-05	3,147E-05
Acidification	-	6,388E-03	5,977E-03	1,616E-04	7,554E-05	1,740E-04
Eutrophication, freshwater	-	1,921E-02	1,745E-02	1,563E-04	4,848E-04	1,123E-03
Eutrophication, marine	-	3,013E-03	2,857E-03	3,006E-05	3,810E-05	8,749E-05
Eutrophication, terrestrial	-	3,418E-03	3,269E-03	3,018E-05	3,624E-05	8,308E-05
Ecotoxicity, freshwater	-	3,470E-02	3,355E-02	3,102E-04	2,547E-04	5,804E-04
Land use	-	3,263E-04	3,100E-04	4,596E-06	3,563E-06	8,129E-06
Water use	-	1,533E-03	1,310E-03	4,517E-05	1,287E-04	4,898E-05
Resource use, fossils	-	1,036E-02	9,393E-03	1,322E-04	2,559E-04	5,838E-04
Resource use, minerals and metals	-	3,937E-03	3,785E-03	4,532E-05	3,413E-05	7,251E-05

Table S6. Normalization factors for GA (Gas Atomization) process.

Impact category	**Unit**	**Total**	**Ti-6Al-4V**	**Argon**	**Electricity**
Climate change	-	5,78E-02	7,68E-03	4,75E-02	2,67E-03
Ozone depletion	-	6,27E-04	1,45E-04	4,57E-04	2,52E-05
Ionising radiation	-	5,73E-02	1,07E-03	5,32E-02	2,97E-03
Photochemical ozone formation	-	2,88E-02	6,02E-03	2,16E-02	1,21E-03
Particulate matter	-	2,09E-02	8,79E-03	1,15E-02	6,31E-04
Human toxicity, non-cancer	-	2,15E-02	4,22E-03	1,63E-02	9,09E-04
Human toxicity, cancer	-	1,50E-02	7,56E-03	7,05E-03	3,85E-04
Acidification	-	4,68E-02	6,88E-03	3,78E-02	2,13E-03
Eutrophication, freshwater	-	2,76E-01	2,01E-02	2,42E-01	1,37E-02
Eutrophication, marine	-	2,34E-02	3,29E-03	1,90E-02	1,07E-03
Eutrophication, terrestrial	-	2,29E-02	3,76E-03	1,81E-02	1,02E-03
Ecotoxicity, freshwater	-	1,73E-01	3,86E-02	1,27E-01	7,09E-03
Land use	-	2,24E-03	3,57E-04	1,78E-03	9,94E-05
Water use	-	6,65E-02	1,51E-03	6,44E-02	5,99E-04
Resource use, fossils	-	1,46E-01	1,08E-02	1,28E-01	7,13E-03
Resource use, minerals and metals	-	2,23E-02	4,35E-03	1,71E-02	8,86E-04

Table S7. Weighting factors for HEBM (High Energy Ball Milling) process.

Impact category	**Unit**	**Total**	**Ti-6Al-4V**	**TiC**	**Argon**	**Electricity**
Total	**mPt**	**5,9E+00**	**5,5E+00**	**6,8E-02**	**9,1E-02**	**1,9E-01**
Climate change	mPt	1,5E+00	1,4E+00	1,4E-02	2,0E-02	4,6E-02
Ozone depletion	mPt	8,2E-03	7,9E-03	8,8E-05	5,8E-05	1,3E-04
Ionising radiation	mPt	6,5E-02	4,6E-02	1,4E-03	5,3E-03	1,2E-02
Photochemical ozone formation	mPt	2,6E-01	2,5E-01	2,3E-03	2,1E-03	4,7E-03
Particulate matter	mPt	7,0E-01	6,8E-01	5,8E-03	2,1E-03	4,6E-03
Human toxicity, non-cancer	mPt	7,0E-02	6,8E-02	9,7E-04	6,0E-04	1,4E-03
Human toxicity, cancer	mPt	1,4E-01	1,4E-01	1,6E-03	3,0E-04	6,7E-04
Acidification	mPt	4,0E-01	3,7E-01	1,0E-02	4,7E-03	1,1E-02
Eutrophication, freshwater	mPt	5,4E-01	4,9E-01	4,4E-03	1,4E-02	3,1E-02
Eutrophication, marine	mPt	8,9E-02	8,5E-02	8,9E-04	1,1E-03	2,6E-03
Eutrophication, terrestrial	mPt	1,3E-01	1,2E-01	1,1E-03	1,3E-03	3,1E-03
Ecotoxicity, freshwater	mPt	6,7E-01	6,4E-01	6,0E-03	4,9E-03	1,1E-02
Land use	mPt	2,6E-02	2,5E-02	3,6E-04	2,8E-04	6,5E-04
Water use	mPt	1,3E-01	1,1E-01	3,8E-03	1,1E-02	4,2E-03
Resource use, fossils	mPt	8,6E-01	7,8E-01	1,1E-02	2,1E-02	4,9E-02
Resource use, minerals and metals	mPt	3,0E-01	2,9E-01	3,4E-03	2,6E-03	5,5E-03
Impact category	**Unit**	**Total**	**Ti-6Al-4V**	**TiC**	**Argon**	**Electricity**
Total	**%**	**100**	**94,09**	**1,15**	**1,56**	**3,20**
Climate change	%	100	94,59	0,97	1,35	3,09
Ozone depletion	%	100	96,65	1,07	0,70	1,58
Ionising radiation	%	100	71,04	2,17	8,16	18,63
Photochemical ozone formation	%	100	96,48	0,90	0,80	1,82
Particulate matter	%	100	98,21	0,83	0,30	0,66
Human toxicity, non-cancer	%	100	95,83	1,37	0,85	1,94
Human toxicity, cancer	%	100	98,22	1,10	0,21	0,47
Acidification	%	100	93,56	2,53	1,18	2,72
Eutrophication, freshwater	%	100	90,82	0,81	2,52	5,85
Eutrophication, marine	%	100	94,83	1,00	1,26	2,90
Eutrophication, terrestrial	%	100	95,63	0,88	1,06	2,43
Ecotoxicity, freshwater	%	100	96,70	0,89	0,73	1,67
Land use	%	100	95,01	1,41	1,09	2,49
Water use	%	100	85,46	2,95	8,40	3,19
Resource use, fossils	%	100	90,62	1,28	2,47	5,63
Resource use, minerals and metals	%	100	96,14	1,15	0,87	1,84

Table S8. Weighting factors for GA (Gas Atomization) process.

Impact category	**Unit**	**Total**	**Ti-6Al-4V**	**Argon**	**Electricity**
Total	**mPt**	**5,42E+01**	**6,34E+00**	**4,56E+01**	**2,29E+00**
Climate change	mPt	1,22E+01	1,62E+00	1,00E+01	5,62E-01
Ozone depletion	mPt	3,96E-02	9,14E-03	2,88E-02	1,59E-03
Ionising radiation	mPt	2,87E+00	5,35E-02	2,67E+00	1,49E-01
Photochemical ozone formation	mPt	1,38E+00	2,88E-01	1,03E+00	5,76E-02
Particulate matter	mPt	1,87E+00	7,87E-01	1,03E+00	5,66E-02
Human toxicity, non-cancer	mPt	3,95E-01	7,77E-02	3,01E-01	1,67E-02
Human toxicity, cancer	mPt	3,19E-01	1,61E-01	1,50E-01	8,19E-03
Acidification	mPt	2,90E+00	4,26E-01	2,34E+00	1,32E-01
Eutrophication, freshwater	mPt	7,73E+00	5,62E-01	6,79E+00	3,84E-01
Eutrophication, marine	mPt	6,93E-01	9,73E-02	5,64E-01	3,17E-02
Eutrophication, terrestrial	mPt	8,49E-01	1,40E-01	6,72E-01	3,77E-02
Ecotoxicity, freshwater	mPt	3,32E+00	7,41E-01	2,45E+00	1,36E-01
Land use	mPt	1,78E-01	2,83E-02	1,41E-01	7,89E-03
Water use	mPt	5,66E+00	1,28E-01	5,48E+00	5,09E-02
Resource use, fossils	mPt	1,21E+01	8,99E-01	1,06E+01	5,94E-01
Resource use, minerals and metals	mPt	1,68E+00	3,29E-01	1,29E+00	6,69E-02
Impact category	**Unit**	**Total**	**Ti-6Al-4V**	**Argon**	**Electricity**
Total	**%**	**100**	**11,70**	**84,07**	**4,23**
Climate change	%	100	13,28	82,11	4,61
Ozone depletion	%	100	23,10	72,88	4,02
Ionising radiation	%	100	1,86	92,95	5,19
Photochemical ozone formation	%	100	20,89	74,93	4,19
Particulate matter	%	100	42,02	54,97	3,02
Human toxicity, non-cancer	%	100	19,66	76,11	4,23
Human toxicity, cancer	%	100	50,40	47,04	2,57
Acidification	%	100	14,70	80,75	4,55
Eutrophication, freshwater	%	100	7,27	87,76	4,97
Eutrophication, marine	%	100	14,04	81,39	4,57
Eutrophication, terrestrial	%	100	16,42	79,14	4,43
Ecotoxicity, freshwater	%	100	22,31	73,59	4,10
Land use	%	100	15,94	79,62	4,44
Water use	%	100	2,27	96,83	0,90
Resource use, fossils	%	100	7,41	87,70	4,89
Resource use, minerals and metals	%	100	19,52	76,51	3,97

5. Ex-ante LCA methodology development: a case study in additive manufacturing gearbox production.

As new technologies emerge is necessary to assess if they can actually contribute to sustainable improvement of industrial processes. Life Cycle Assessment (LCA) is a valuable tool to determine environmental impacts and compare systems. However, this comparison raises challenges when they have different maturity. This study performs ex-ante LCA of an additive manufacturing (AM) technology, based on a step-wise approach built with parametrized modelling, allowing fair comparison with its conventional counterpart, for the study case of a gearbox component. Results show that AM technology generates higher impacts than conventional manufacturing (CM) casting process, using baseline values. These impacts can be reduced by 94% with best operating performances from literature, with non-significant difference with CM (demonstrated by Monte Carlo sampling). A 58% weight reduction is necessary for the AM process to improves its environmental sustainability. This research provides eco-design recommendations supporting decision making for further development of new technology.

5.1. Introduction.

The industrial sector represents a significant environmental pressure, with 22% of the total greenhouse gas emissions at European level (European Environment Agency (2021) and 29% of the total energy consumption at worldwide level (International Energy Agency, 2019). It is therefore necessary to improve the sustainability of industrial processes (Paul et al., 2022) and adopt new technologies to do so. The deployment of additive manufacturing (AM) can play an important role towards this transition (Ford & Despeisse, 2016; J. Ma et al., 2018; Agrawal & Vinodh, 2019).

AM, which is defined as “process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies” by ASTM and ISO standards (ISO/ASTM 52900:2021), can reduce resource, energy and waste, reconfigure supply chains and produce more efficient designs (Peng et al., 2018; Daraban et al., 2019). Combining such advanced technology with new performant materials such as Metal Matrix Composites (MMCs) can further reduce emissions (Ferreira et al., 2019). MMCs, composed of metal and additional component(s) such as ceramics with high strength, wear resistance, fatigue or other specific properties (Vijaya Ramnath et al., 2021), can represent a promising lightweight and sustainable alternative for the automotive industry (Dadkhah et al., 2021).

To demonstrate the sustainability of these developing technologies, it is necessary to compare their environmental impact with conventional technologies, via the comprehensive Life Cycle Assessment (LCA) methodology (Paris et al., 2016). Up to now, only a few studies performed such evaluation. Paris et al., (2016) compared the environmental impacts of a Ti6AlV turbine made by a subtractive conventional manufacturing (CM) process with an AM technique called Electronic Beam Melting (EBM) with a not completely optimized geometry, based on primary process data. The results showed lower impacts for the AM technology, in particular in the case of complex shapes (high material removal). Ingarao et al., (2018) created different geometry scenarios for aluminium alloys, using bibliography data, and showed that the AM technology is suitable in terms of sustainability when the weight is reduced by 50% and even more if the use phase is included in the scope. The benefits of AM process were also shown in (Ingarao & Priarone, 2020) for Ti6Al4V components, using a partially parametrized model and data from literature, with a better energy efficiency thanks to the lower amount of input material used. A study by van Sice & Faludi, (2021) used information to simulate various CM and AM techniques from a database and from literature review, respectively, to compare the manufacturing of steel, aluminium and titanium parts. The authors concluded that AM processes generated higher impacts when focusing only on the manufacturing process, while the further effects on mass reduction and design need to be considered to improve their sustainability. Landi et al., (2022) analysed and compared the environmental impacts of an AM technology with a subtractive CM, using primary data obtained from direct measurements in the production process of spur gears made of steel alloy, obtaining advantages for the AM process, but pointing out that it is still an experimental technology with a lower maturity level than its counterpart. A comparative gate-to-gate LCA was carried out on a software-simulated AM process and a CM industrial method, by Swetha et al., (2022), obtaining that an optimization on the component's topology it is necessary to obtain a more environmentally friendly process.

These studies relied on both the collection of primary data and process simulation. Due to the low maturity of AM technologies, it is important to consider upscaling changes to get a fair comparison with mature CM technologies (Wender et al., 2014, Villares et al., 2017, Buyle et al., 2019). For this purpose, several frameworks with different scopes and definitions have emerge in recent times: (i) Wender et al., (2014) introduced the idea of anticipatory LCA as a "forward-looking, non-predictive tool that increases model uncertainty through inclusion of prospective modelling tools and multiple social perspectives”; (ii) Arvidsson et al., (2018) stated that “an LCA is prospective when the technology studied is in an early phase of development but the technology is modelled at a future, more-developed phase”; (iii) An ex-ante LCA “explores the future by assessing a range of possible scenarios that define the space in which the emerging technology may operate at future performance on full operational scale” as explained by Cucurachi et al., (2018). Despite the minor differences between them, as the anticipatory LCA included a socioeconomic perspective, and the prospective LCA can be performed on an already established technology, the term ex-ante has been adopted as the preferred one for this study. The use of this expression makes clearer than the assessment can be performed prior market introduction (van der Giesen et al., 2020).

In order to apply an ex-ante LCA and facilitate the creation of exploratory scenarios, parametric modelling built by mathematical correlations to generate the material and energy balances and focused on the most influencing parameters, can be introduced. A parametric framework was applied by Yao & Huang (2019) for the identification of research development priorities but this study only focuses on energy and cost assessment, without a comparative purpose. In literature, some parametrized LCA studies were used to evaluate and support the eco-design of emerging technologies in other sectors (e.g. Elginoz et al., 2022; Prézélus et al., 2021) based on process modelling, scenarios building with different parameters values and sensitivity analysis to identify the key parameters.

The present paper builds on these ex-ante parametric LCA approaches to evaluate the environmental impacts of AM technologies compared to CM processes for the case study of gearbox components. The methodological approach, based on parametric modelling and further analyses (sensitivity, break-even point and uncertainty), is first described, while the results for the case study are further analysed and discussed.

5.2. Methodology.

To support the design of an AM technique with environmental criteria, a stepwise approach based on the standardised LCA methodology (ISO 14040/44, 2006) is followed.

First, a parametrized inventory model is built for the AM technique, expressing relationships between dependant parameters, using technology prototype data as baseline values for the independent variables. Then, scale-up scenarios are defined. To do so, the most influential parameters are identified via sensitivity analysis. Based on a literature review and expert knowledge, the best available values for the sensitive independent parameters that could be affected by the upscale of the technology are determined (e.g. best efficiency rates obtained by similar technologies). The literature values are used to model the best scenario of the AM technique. The results analysis includes several techniques. Besides the contribution and sensitivity analyses identifying the key processes and parameters, the calculation of break-even point values is performed to determine the target value of a parameter that allows the AM technique to generate less environmental impacts than the conventional alternative. These outcomes can therefore support the eco-design of the technology by prioritizing efforts and defining design objectives. Finally, a comparative uncertainty analysis (based on

Monte Carlo sampling) of the scenarios is applied to understand the robustness of the potential environmental benefits and trade-offs of the AM technique.

The modelling is done in SimaPro® 9.3 software, using parameters, scenarios and uncertainty analysis functions.

5.2.1. Study case.

Two different technologies are assessed in this study, both capable to produce the same gearbox component. The first one is a conventional technology, already implemented in the market. It uses aluminium that goes first through casting, followed by different steps of refining such as deburring, sand cleaning and heat treatment, each of them with a different performance over the material quantity, using auxiliary materials as water, sand and oil. The second technology assessed is an AM technique called Directed Energy Deposition, where the powder material fed is fused by a laser, placed on a robotic arm, which deposits the material over a metallic plate to make the desired form, while is controlled by a computer with the 3D design. This operation takes place under a vacuum chamber filled with argon to avoid any oxygen reaction with the metal that can cause problems during the manufacturing process. The printing process is carried out on a titanium metal plate, which varies in shape and size depending on the part to be manufactured in each process. The powder material used is a Titanium Matrix Composite made from alpha-beta titanium alloy (Ti6Al4V) and titanium carbide (TiC) nanoparticles, produced in a High Energy Ball Milling process. This alloy provides high-quality properties: strength to weight ratio, corrosion resistance, biocompatibility, and low thermal expansion (Gökelma et al., 2018), and the TiC ceramic particles apport functionalities as its high melting point, elastic modulus, high hardness, low density, high flexure strength, good thermal conductivity, high resistance to corrosion and oxidation, and high thermal shock resistance (Mhadhbi, 2020). A complete LCA study of the production route for this powder has been studied by Santiago-Herrera et al. (2022).

5.2.2. Goal and scope of the LCA study.

The main aim of this study is to evaluate and compare the environmental performance of two different technologies, capable to produce a gearbox component for automobiles: (i) a conventional manufacturing technology based on casting, and; (ii) an additive manufacturing one using the DED technique.

Figures 13 and 14 represents the system boundaries for CM and AM processes, respectively. The systems boundaries are focused on the production phase of the gearbox component, including all the specific processes constituting the foreground data, and background data retrieved from databases. It also incorporates the use phase, in order to analyse potential benefits of the AM component depending on its potential weight savings. The use phase is modelled only for the calculation of the break-even point distance depending on the component mass reduction and associated fuel savings. End-of-Life is not included due to the lack of data at this stage of the project. Infrastructures components are also excluded from this study.

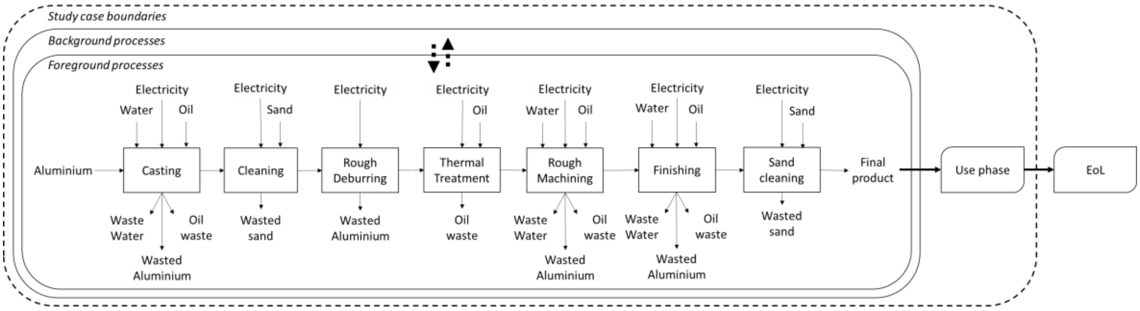

Figure 13. Flow model and system boundaries of the conventional manufacturing technology.

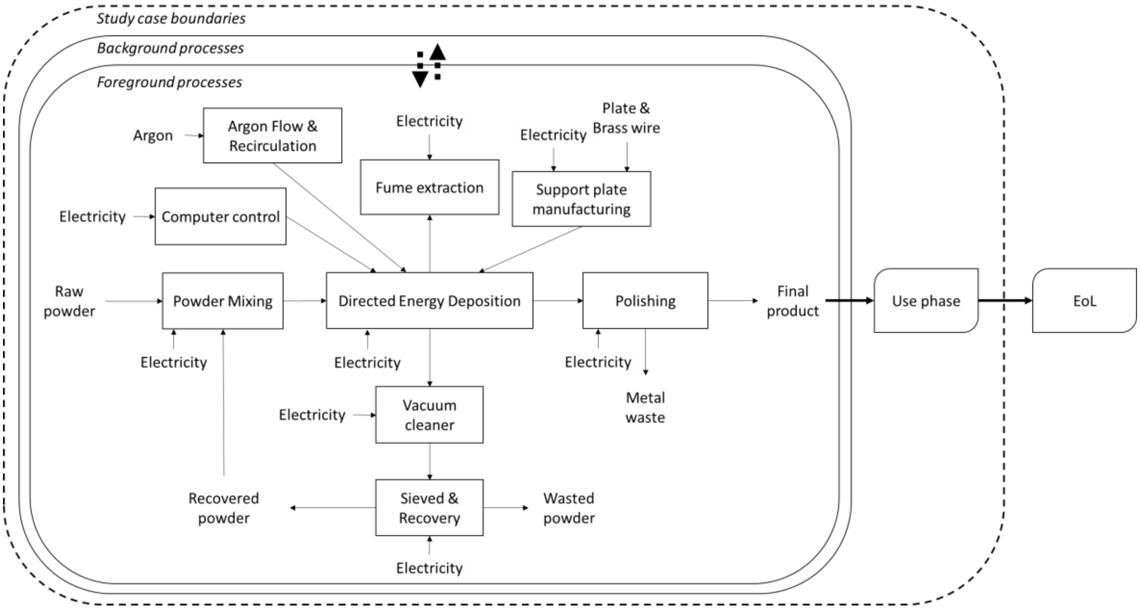

Figure 14. Flow model and system boundaries of the additive manufacturing technology.

The function of the assessed systems is the production of one complete piece. Due to the uncertainties on final weight and properties of the manufactured piece at such development stage, the comparison is primarily done on a mass unit basis, which is a tangible unit which facilitates mass balance. The functional unit is therefore the manufacturing of 1 kg of piece. The further sensitivity analysis will analyse the possible weight differences between AM and CM and the effects on impact results.

The geographical representativeness of the study is set under the European framework.

5.2.3. Life Cycle Inventory.

Production data, obtained during the 2021-2022 period from two European industrial partners from the automotive sector, are used as a basis for the foreground inventory data. Background processes are modelled with ecoinvent v3.8 database and “APOS” system model (at the point of substitution), to adopt an attributional approach while extending the system boundaries to allocate co-products burdens (Wernet et al., 2016). The different chosen datasets are shown on Supplementary Material, Table S1&S2.

The following sub-sections detail the development of the parametrised model for the determination of foreground data, the definition of parameters values and their uncertainty, and the construction of different scenarios.

5.2.3.1. Development of the parametrised model.

The aim of the parametrised model is to determine the foreground inventory flows based on the energy and mass balance, and their common relationships. The independent parameters are fixed with numerical values, while dependent parameters are calculated according to the independent ones (see Table 8).

For the CM case, fixed parameters are set for the specific energy consumption data per kg of product since their characterization is based on mature technology data, although the values are still subject to uncertainties. Regarding the input of alloy as raw material, the losses during casting, deburring, machining and finishing are considered. The efficiencies of these processes (in %) are used to calculate the necessary amount of input alloy for the functional unit, i.e., 1 kg of final product. Regarding water, oil and sand flows, the input flows are set with primary data and no losses are assumed during the processes.

Regarding the AM technology, the specific energy consumption is more uncertain. For each step, the latter (e.g. $E_{Support\ plate}$) is derived from the machine power (e.g. $P_{Supplort\ plate}$) and the processing time (e.g. $t_{Support\ plate}$). The processing times are mostly independent, while the printing step depends on the mass of input power ($m_{powder,total}$). The printing time t_{DED}, in straight relation with the Directed Energy Deposition process, is calculated from the ratio between

$m_{powder,total}$ and the flow rate r_{Flow}, and influences the energy consumption of other processes. For instance, it affects the mixing step, since the powders are mixed and introduced during the entire printing process. It also affects polishing, the vacuuming and sieving of the undeposited powders, as it is stressed by a mathematical expression indicated by manufacturers. Argon is used for the blowing and the printing steps. The total volume of argon used in the chamber $V_{Ar,total}$ is the product of the argon flow and the processing time for these two steps ($Q_{Blowing}$ (1200 L/h) and $t_{Blowing}$, Q_{DED} (900 L/h) and t_{DED}, respectively). The argon recirculation rate $r_{Recirculation}$ is applied to calculate the necessary input of argon $V_{Ar,in}$. The necessary input of raw powder ($m_{powder,in}$) depends on the polishing and deposition efficiencies, based on the final product weight, $m_{final,AM}$. To obtain the total mass, $m_{powder,total}$, it is necessary to add a maximum of 5% coming from the recovering process ($m_{powder,recovered}$), to not downgrade the quality of the printed piece. This corresponds to the quantity of powder not deposited but aspirated by the vacuum cleaner process ($m_{powder,vacuum}$) which is sieved later, at a 92.5% efficiency, obtaining $m_{powder,sieved}$ that can be used to feed the system again. All these calculations are presented in Table 8.

Table 8. List of model parameters and their determination.

Flow type	Parameter	Fixed[a]	Definition
Conventional Manufacturing			
Energy consumption	$E_{Casting}$	X	
	$E_{Cleaning1}$	X	
	$E_{Deburring}$	X	
	$E_{Thermal}$	X	
	$E_{Machining}$	X	
	$E_{Finishing}$	X	
	$E_{Cleaning2}$	X	
Materials inputs[b]	$m_{alloy,in}$		$m_{alloy,in} = (((m_{final,CM}/\eta_{Finishing})/\eta_{Deburring})/\eta_{Machining})/\eta_{Casting}$
	$m_{sand,in}$	X	
	$m_{oil,in}$	X	
	$m_{water,in}$	X	
Waste amount[c]	$m_{alloy\ waste}$		$m_{alloy\ waste} = m_{alloy,in} - m_{final,CM}$
	$m_{sand\ waste}$		$m_{sand\ waste} = m_{sand,in}$
	$m_{oil\ waste}$		$m_{oil\ waste} = m_{oil,in}$
	$m_{wastewater}$		$m_{wastewater} = m_{water,in}$
Additive Manufacturing			
Energy consumption	E_{Mixing}		$E_{Mixing} = P_{Mixing} \times t_{DED}$ with $t_{DED} = m_{powder,total}/r_{flow}$
	E_{DED}		$E_{DED} = (P_{DED1} + P_{DED2}) \times t_{DED}$
	$E_{Polishing}$		$E_{Polishing} = P_{Polishing} \times t_{Polishing}$ with $t_{Polishing} = (t_{DED}/9.5) \times 4$
	E_{Vacuum}		$E_{Vacuum} = P_{Vacuum} \times t_{Vacuum}$ with $t_{Vacuum} = (t_{DED}/9.5)$
	E_{Sieved}		$E_{Sieved} = P_{Sieved} \times t_{Sieved}$ with $t_{Sieved} = (t_{DED}/9.5)$
	$E_{Computer}$		$E_{Computer} = P_{Computer} \times t_{DED}$
	E_{Fume}		$E_{Fume} = P_{Fume} \times t_{DED}$
	$E_{Support\ plate}$		$E_{Support\ plate} = P_{Supplort\ plate} \times t_{Support\ plate}$
Materials inputs	$m_{powder,total}$		$m_{powder,total} = (m_{final,AM}/\eta_{Polishing})/\eta_{DED}$
	$m_{powder,in}$		$m_{powder,in} = m_{powder,total} \times 0.95$
	$m_{powder,not\ used}$		$m_{powder,not\ used} = m_{powder,total} \times (1 - \eta_{DED}) = m_{powder,vacuum}$
	$m_{powder,vacuum}$		
	$m_{powder,sieved}$		$m_{sieved} = m_{powder,vacuum} \times 0.925$
	$m_{Support\ plate}$	X	
	$V_{Ar,total}$		$V_{Ar,total} = (Q_{Blowing} \times t_{Blowing} + Q_{DED} \times t_{DED})$
	$V_{Ar,in}$		$V_{Ar,in} = V_{Ar,total} - (r_{Recirculation} \times V_{Ar,total})$
Waste amount	$m_{powder\ waste}$		$m_{powder\ wasted} = m_{powder,vacuum} \times 0.075$
	$m_{metal\ waste}$		$m_{metal\ waste} = (m_{final,AM}/\eta_{Polishing}) \times (1 - \eta_{Polishing})$

[a] Fixed parameter are marked with and “X”.

[b] Sand, oil and water inputs are introduced in different quantities at each stage of the process, so they are named differently, as presented in Table 9.

[c] Waste amounts are different in each stage of the process as in relation with each material input.

5.2.3.2. Definition of parameters values.

This sub-section explores the determination of independent parameters, both for baseline scenarios and for scaled-up scenarios in the AM case.

Baseline values were obtained with the help of two different industrial manufacturers, representing data collected during the 2021-2022 period. These baseline values, for both technologies are included in Tables 9&10.

Table 9. Conventional Manufacturing technology data of parameters, values and uncertainty factors.

Conventional Manufacturing								
				Pedigree Matrix				
Parameters	Unit	Baseline values	Basic uncertainty	Reliability	Completeness	Temporal correlation	Geographical correlation	Further technological correlation
$E_{Casting}$	kWh	243	0.0006	1	4	1	1	1
$m_{water,Casting}$	kg	1.43	0.0006	1	4	1	1	1
$m_{oil,Casting}$	kg	0.071	0.0006	1	4	1	1	1
$\eta_{Casting}$	%	0.8	0.0006	1	4	1	1	1
$m_{sand,Cleaning1}$	kg	0.071	0.0006	1	4	1	1	1
$E_{Cleaning1}$	kWh	0.14	0.0006	1	4	1	1	1
$E_{Deburring}$	kWh	0.071	0.0006	1	4	1	1	1
$\eta_{Deburring}$	%	0.975	0.0006	1	4	1	1	1
$E_{Thermal}$	kWh	0.71	0.0006	1	4	1	1	1
$m_{oil,Thermal}$	kg	0.071	0.0006	1	4	1	1	1
$E_{Machining}$	kWh	0.5	0.0006	1	4	1	1	1
$m_{water,Machining}$	kg	0.71	0.0006	1	4	1	1	1
$m_{oil,Machining}$	kg	0.035	0.0006	1	4	1	1	1
$\eta_{Machining}$	%	0.84	0.0006	1	4	1	1	1
$E_{Finishing}$	kWh	0.57	0.0006	1	4	1	1	1
$m_{water,Finishing}$	kg	1.43	0.0006	1	4	1	1	1
$m_{oil,Finishing}$	kg	0.035	0.0006	1	4	1	1	1
$\eta_{Finishing}$	%	0.85	0.0006	1	4	1	1	1
$E_{Cleaning2}$	kWh	0.14	0.0006	1	4	1	1	1
$m_{sand,Cleaning2}$	kg	0.071	0.0006	1	4	1	1	1

Table 10. Additive Manufacturing technology data of parameters, values and uncertainty factors.

Additive Manufacturing								
				Pedigree Matrix				
Parameters	Unit	Baseline values	Basic uncertainty	Reliability	Completeness	Temporal correlation	Geographical correlation	Further technological correlation
$t_{Support\ plate}$	h	4.50	0.0006	2	4	1	1	2
$P_{SupportPlate}$	kW	17.7	0.0006	2	4	1	1	2
P_{Mixing}	kW	0.22	0.0006	1	4	1	1	1
P_{DED1}	kW	0.58	0.0006	1	4	1	1	1
P_{DED2}	kW	0.68	0.0006	1	4	1	1	1
$P_{Computer}$	kW	0.16	0.0006	1	4	1	1	1
P_{Vacuum}	kW	1.2	0.0006	1	4	1	1	1
P_{Sieved}	kW	0.2	0.0006	1	4	1	1	1
$P_{Polishing}$	kW	0.2	0.0006	2	4	1	1	2
P_{Fume}	kW	0.02	0.0006	1	4	1	1	1
$m_{Supplort\ plate}$	kg	1.8	0.0006	2	4	1	1	2
$m_{Brass\ wire}$	kg	4	0.0006	2	4	1	1	2
$r_{Flow}{}^*$	kg/h	0.525	0.0006	4	4	2	3	3
$\eta_{Deposition}{}^*$	%	0.43	0.0006	4	4	2	3	3
$\eta_{Polishing}{}^*$	%	0.65	0.0006	4	4	2	3	3
$t_{Blowing}$	h	1.5	0.0006	1	4	1	1	1
$r_{Recirculation}{}^*$	%	0.724	0.0006	4	4	2	3	3

Note: Parameters with * are the ones affected by the upscale approach, with changes in their baseline values.

For additive manufacturing, the parameters include the fixed mass data (for support plate and brass wire), flow rates of the powder, recirculation and efficiency rates, the power of the different used machines and the time for specific processes (blowing and on support plate). The time of deposition process (t_{DED}) is derived from the total mass of powder ($m_{powder,total}$) and the powder feeding rate (r_{Flow}): t_{DED} = $m_{powder,total}/r_{flow}$.

As mentioned in the Introduction section, the technologies of this study cannot be totally comparable under the LCA framework as they are not at the same level of maturity. However, some aspects of the AM technology are expected to be improved in the future with the optimization of the process performance. For this purpose, a set of the previously build-up parameters were selected, as they were the most likely to be improved in a forthcoming developed scenario and can vary more substantially the final outcome results, as can be seen in the sensitivity analysis results section:

- "r_{Flow}": is the flow rate, which express the quantity of powder fed into the system that can be possible processed, within a set of time, measured in kg/h.
- "$\eta_{Deposition}$": measuring the powder utilization efficiency by the laser melting process (in %).
- "$r_{Recirculation}$": the argon recirculation rate inside the vacuum chamber where the 3D printing process takes part (in %).
- "$\eta_{Polishing}$": as the successfully reduced surface roughness to obtain a final component (%).

A comprehensive literature review on the state-of-the-art for the assessed AM technique (Directed Energy Deposition), using the same or similar alloy (Titanium grade 5), was performed to understand the range for these parameters, support the creation of prospective scenarios and prioritize efforts for future improvements.

The retrieved information (Table 11) shows possible scenarios where r_{Flow} could be up to 3.6 kg/h, $\eta_{Deposition}$ to 90%, $\eta_{Polishing}$ rises up to a 95%, and a highest point of 98% for the $r_{Recirculation}$ is achieved. Therefore, a final scenario with these values was set for the AM technology as the most promising scenario in a higher mature level with an optimistic development process.

Table 11. Overview of the literature review for the parametric variables prospective data.

Reference	Technology & Material	Maturity level	Variable parameters	Values
Lia et al., 2018	Directed Energy Deposition and Ti-6Al-4V	Lab-scale	r_{Flow}	0.81kg/h
Niknam et al., 2018	Directed Energy Deposition and Ti-6Al-4V	Full scale	r_{Flow}	1.8 and 3.6 kg/h
Keist & Palmer, 2016	Directed Energy Deposition and Ti-6Al-4V	Lab-scale	r_{Flow}	0.72 kg/h
Qiu et al., 2015	Directed Energy Deposition and Ti-6Al-4V	Prototype	r_{Flow}	0.36-0.96 kg/h
Wolff et al., 2021	Directed Energy Deposition and Ti-6Al-4V	Industrial scale	r_{Flow}	2.52 kg/h
Carrozza et al., 2021	Directed Energy Deposition and Ti-6Al-4V	Lab-scale	$\eta_{Deposition}$	60% - 84.3%
Serres et al., 2011	Directed Energy Deposition and Ti-6Al-4V	Full scale	$\eta_{Deposition}$	65% - 90%
Mahamood & Akinlabi, 2016	Directed Energy Deposition and Ti-6Al-4V	Lab-scale	$\eta_{Deposition}$	70% - 90%
Tian et al., 2018	Laser polishing on Electron Beam Melted Ti6Al4V component	Lab-scale	$\eta_{Polishing}$	75%
Gora et al., 2016	Laser polishing on Selective Laser Melting Ti6Al4V component	Lab-scale	$\eta_{Polishing}$	85%
Marimuthu et al., 2015	Laser polishing on Selective Laser Melting Ti6Al4V component	Lab-scale	$\eta_{Polishing}$	76%.
Ma et al., 2017	Laser polishing on Additive Manufacturing Ti6Al4V component	Lab-scale	$\eta_{Polishing}$	80%
Nesli & Yilmaz, 2021	Laser polishing on Electron Beam Melted Ti6Al4V component	Lab-scale	$\eta_{Polishing}$	75.1% - 91.6%
Li et al., 2019	Laser polishing on Selective Laser Melting Ti6Al4V component	Lab-scale	$\eta_{Polishing}$	95%
Genna & Rubino, 2019	Laser polishing on Electron Beam Melted Ti6Al4V component	Lab-scale	$\eta_{Polishing}$	80
Martorell et al., 1999	Gas recycling loop	Prototype	$r_{Recirculation}$	85%
Wilson et al., 2013	Recycling system for Gas Atomization process	Full scale	$r_{Recirculation}$	97.8%
Tirk et al., 2016	Gas Recycling in Inductively Coupled Plasma Optical Emission Spectrometry	Prototype	$r_{Recirculation}$	90%

5.2.3.3. Uncertainty characterization.

The uncertainty of a system expresses the lack of confidence in the representativeness of the true value of a parameter (Muller et al., 2016). Despite it is a necessary step to determine the reliability of the results and it is recommended by ISO standards, it is still not widespread among LCA studies (Igos et al., 2019).

Due to the lack of statistical data, the ecoinvent database guideline from Weidema et al. (2013) was used to generate the uncertainty distribution of parameters. Here, two different kinds of uncertainty are presented: basic uncertainty, which reflect the intrinsic variability, and the additional uncertainty, due to the use of imperfect data.

The lognormal is the common distribution in the ecoinvent database, because it allows multiplicative effects and is a skewed distribution without negative values. The geometric mean (μ_g) and the geometric standard deviation (σ_g) define the distribution, with the latter determining the uncertainty (Muller et al., 2016).

The aforementioned guideline provides the values of both uncertainty types, expressed as the square of the geometric standard deviation. For the basic uncertainty, ecoinvent defines default values depending on the type of flow, which are here the same for all parameters (process mass and energy flows). The pedigree matrix was used for the additional uncertainty, where an uncertainty value is assigned for five different quality indicators ("reliability", "completeness", "temporal correlation", "geographic correlation", and "further technological correlation") with a score between 1 to 5. The selection is based on the reliability of the data sources, being slightly higher for the assessed variable parameters.

These applied uncertainty factors are included in Tables 9 and 10, for both technologies assessed.

These different values can be add up expressing the dispersion around the mean, based on the standard deviation under a 95% interval confidence (SD_{g95}), which is the square of the geometric standard deviation, as can be seen in Eq.1:

$$SD_{g95} \cong \sigma_g^2 = exp^{\sqrt{[\ln(U_1)]^2+[\ln(U_2)]^2+[\ln(U_3)]^2+[\ln(U_4)]^2+[\ln(U_5)]^2+[\ln(U_b)]^2}} \qquad (1)$$

where U_1=uncertainty factor of reliability, U_2=uncertainty factor of completeness, U_3=uncertainty factor of temporal correlation, U_4=uncertainty factor of geographic correlation, U_5=uncertainty factor of further technological correlation, and U_b=basic uncertainty factor.

In addition, the uncertainty included in the datasets of the background processes is also considered.

5.2.4. Life cycle impact assessment.

The evaluation of environmental impacts is done in SimaPro® 9.3 with the EF 3.0 method. The latter is based on the Environmental Footprint (EF) initiative, launched by the European Commission to create a harmonised EU methodology to communicate environmental performance of products or organisations (European Commission, 2013). This method consists of 16 midpoint impact categories, extracted from Fazio et al., (2018): Climate change (kg CO2 eq.), Ozone depletion (kg CFC11 eq.), Ionising radiation (kBq U-235 eq.), Photochemical ozone formation (kg NMVOC eq.), Particulate matter (disease incidence), Human toxicity, non-cancer (CTUh), Human toxicity, cancer (CTUh), Acidification mol (H+ eq.), Eutrophication, freshwater (kg P eq.), Eutrophication, marine (kg N eq.), Eutrophication, terrestrial (mol N eq.), Ecotoxicity, freshwater (CTUe), Land use (Pt), Water use (m3 deprived), Resource use, fossils (MJ) Resource use, minerals and metals (kg Sb eq.).

In order to obtain a single score of the environmental impacts to facilitate the comparison of technologies, two steps are necessary: normalization, to convert the impacts in a common unit scale, expressing the total impact occurring in a reference region for a certain impact category within a reference year, based on Crenna et al., (2019); and weighting, to consider the relevance and reliability of indicators, based on Sala et al., (2018).

5.2.4.1. Calculation of sensitivity index.

One-at-a-time variations were performed for the independent parameters, on their uncertainty range. The sensitivity index (S.I.) is calculated for each parameter, as the ratio between the percentage of change in the output's impact category (∆IC) over the percentage change of the variable increased value (∆VI), as shown in Eq.2:

$$S.I. = \frac{\Delta IC}{\Delta VI} \tag{2}$$

The higher the S.I., the more sensitive are the results to the parameter.

5.2.4.2. Break-even point.

Since the AM technology is supposed to produce lighter pieces, the mass reduction factor required to obtain environmental benefits compared to the conventional technology, is calculated. This factor, expressed as a percentage, corresponds to the relative difference between the impact of CM technology (I_{CM})

and the one of AM technology (I_{AM}) (see Eq. 3). This break-even point is calculated at single score level using the best-case AM scenario.

$$Weight\ Decrease \geq \frac{I_{CM} - I_{AM}}{I_{AM}} \tag{3}$$

5.2.4.3. Monte Carlo simulation.

In order to propagate the input uncertainty, explained in section 6.2.3.3, into output uncertainty, the Monte Carlo sampling method was applied. This method makes a large number of calculations which provides a probabilistic range to understand the uncertainty of the impacts results (Heijungs & Kleijn, 2001). A sampling with 10,000 simulations was applied in this study. A discernibility analysis was performed to consider the common uncertain parameters and determine the number of simulations when one technology has a higher impact that its counterpart.

5.2.4.4. Use phase modelling.

As final step, it was decided to assess the operational step of the final component, to find the Break Even Distance (BED) when the new technology could start to be feasible. For this, the calculation presented in Salonitis et al. (2019) was modified by changing energy burdens with single score impact, as shown in Eq. 4:

$$BED = \frac{\Delta Ip}{(\delta F_s \times I_{FC} \times \Delta m)} \times 10^4 \tag{4}$$

where ΔIp: Impact difference between both technologies for a given weight (e.g. in mPts/kg);

δF_s: Fuel savings per weight reduction (constant factor of 0.2 L/km·kg);

I_{FC}: Impact of fuel consumption (e.g. in mPts/L fuel);

Δm: Product weight difference between both technologies (in kg).

Finally, to find a reasonable distance where the new technology could be less environmental impactful, different AM component weights will be tested.

5.3. Results.

The outcomes of the study reflect the comparative analysis between both technologies, using the step-wise methodology presented. The impacts are shown in the weighting single-score, in mPts, to facilitate its interpretation, but more specific data with unnormalized impact factors can be found in the Supplementary Material, Tables S3, S4&S5.

5.3.1. Baseline comparative and contribution analysis of each technology.

Firstly, the processes were assessed in their baseline values, to compare both at current state, as presented in Figure 15. The single score of CM is almost 13 mPts, mainly due to energy use (79% of contribution), while more than 530 mPts are obtained for the AM technology (93% of impacts are due to Argon use). Besides energy, the environmental profile of CM process is also influenced by the raw material input of aluminium alloy (19% in single score, with the highest contribution on Particulate matter and Human toxicity cancer, with more than 50% contribution). Regarding AM process, the other process flows have mostly a contribution lower than 10% regardless of the impact category, except for the titanium materials on particulate matter (16%) and human toxicity, cancer. The most impacted categories for the single score are Climate change and Use of fossil resources, for both technologies. These data are detailed on Supplementary Material, Tables S6&S7.

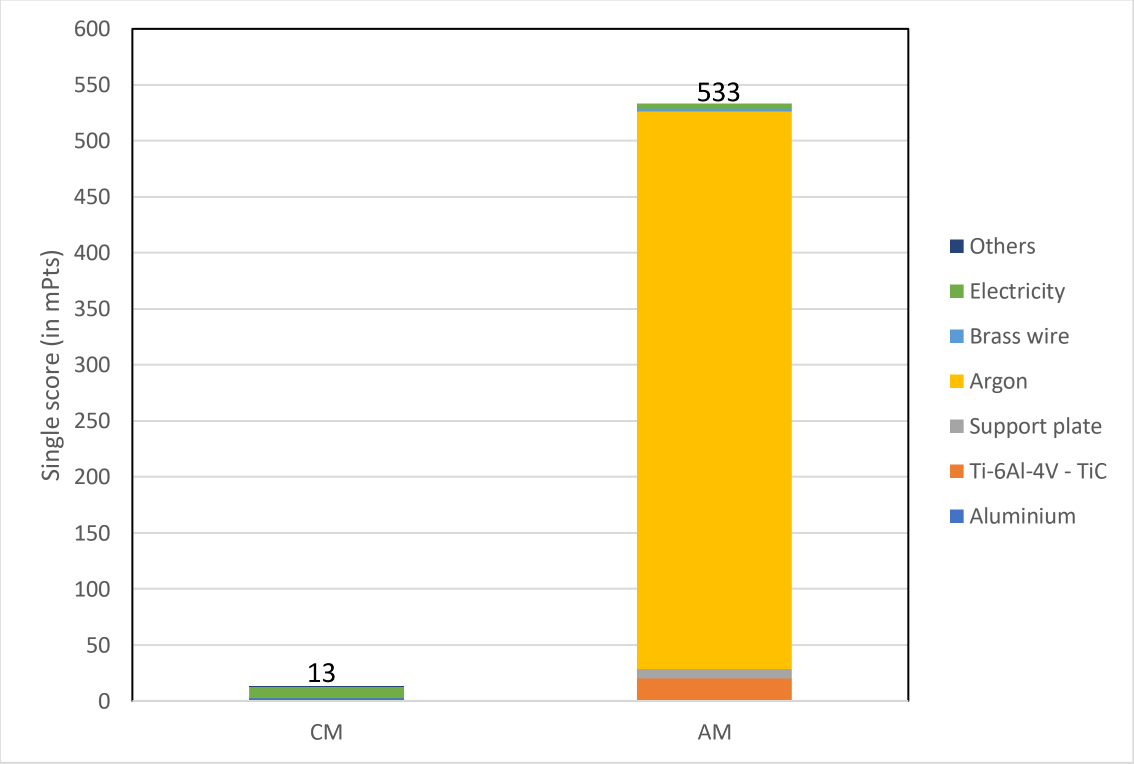

Figure 15. Single score factors for CM (conventional manufacturing) and AM (additive manufacturing) at baseline values.

5.3.2. Sensitivity, scenario and break-even point analysis.

The sensitivity analysis (one-at-a-time variations) was performed for the AM scenario using the data range from literature. The analysis of the four key parameters (r_{Flow}, $\eta_{Deposition}$, $r_{Recirculation}$, $\eta_{Polishing}$) highlighted a negative relationship, i.e. the higher the parameter, the lower the impacts (see Figures S1-S4 in Supplementary Material). Each parameter has a different scale of variations, from +35% compared to the baseline value for $r_{Recirculation}$ to +585% for r_{Flow}. The highest impact variation was observed for $r_{Recirculation}$ (-86% with highest value), leading to a sensitivity index of -2.45, while it is between -0.52 for $\eta_{Polishing}$, -0.36 for $\eta_{Deposition}$ and -0.11 in the case of r_{Flow} parameter. The same trends are observed for all environmental indicators. This outcome means that the recirculation of argon is the most affecting impacting variable of the process and should be optimized in priority to improve the environmental performances of the AM process.

A final best-case scenario is built with the best available data from the state-of-the-art review, obtaining a 94% scoring reduction compared to the baseline value on the single score, with a variation of 81% to 97% reduction depending on the indicator, as it is shown in Table 12.

Table 12. Single score factors for AM (additive manufacturing) best scenario and reduction percentage as compare with baseline values.

Impact category	Unit	Baseline values	Best scenario	Impact reduction
Total	**mPt**	**533**	**31.2**	**-94%**
Climate change	mPt	117	6.87	-94%
Ozone depletion	mPt	0.36	0.03	-91%
Ionising radiation	mPt	29.6	0.93	-96%
Photochemical ozone formation	mPt	12.6	1.01	-92%
Particulate matter	mPt	14.8	2.21	-85%
Human toxicity, non-cancer	mPt	3.74	0.35	-90%
Human toxicity, cancer	mPt	2.39	0.45	-81%
Acidification	mPt	27.8	1.82	-93%
Eutrophication, freshwater	mPt	77.4	3.47	-95%
Eutrophication, marine	mPt	6.66	0.41	-93%
Eutrophication, terrestrial	mPt	8.04	0.54	-93%
Ecotoxicity, freshwater	mPt	30.5	2.77	-90%
Land use	mPt	1.69	0.11	-93%
Water use	mPt	60.5	1.56	-97%
Resource use, fossils	mPt	121	5.35	-95%
Resource use, minerals and metals	mPt	17.8	3.33	-81%

The detailed single score comparison of the best-case AM scenario with CM is shown in Figure 16. Argon use remains with a significant contribution but to a lesser extent (30.5% of single score impact), followed by the production of the titanium support plate (28%) and the titanium powder (21%), as shown in Figure 16. These three flows remain the main sources of all impact types, with some variations depending on the indicator. For example, argon has the highest impact on ionising radiation and water use (60% and 74%, respectively), the support plate on carcinogenic impacts, particulate matter, ozone depletion (50%, 49% and 42%, respectively) and the titanium powder on particulate matter and human toxicity, cancer (35%). The only indicator for which these flows have a minor effect is the use of mineral and metallic resources, for which brass contributes to 57% of the production impacts (mainly due to tellurium extraction for the production of copper cathode used for brass manufacturing). The consumption of electricity never dominates the impact, but has a non-negligible contribution, between 5% and 24% depending on the indicator. Once the best values for the four key parameters could be reached, the further improvement of all process flows is thus important. These conclusions are valid for 1 kg of gearbox piece; however, the AM process normally leads to weight reduction. Using Eq.3 and the total impact in mPts, the weight reduction needed in the AM components to be at least equal to its counterpart's impact is 58% for the best-case scenario. More detailed data can be found in Supplementary Material, Table S8.

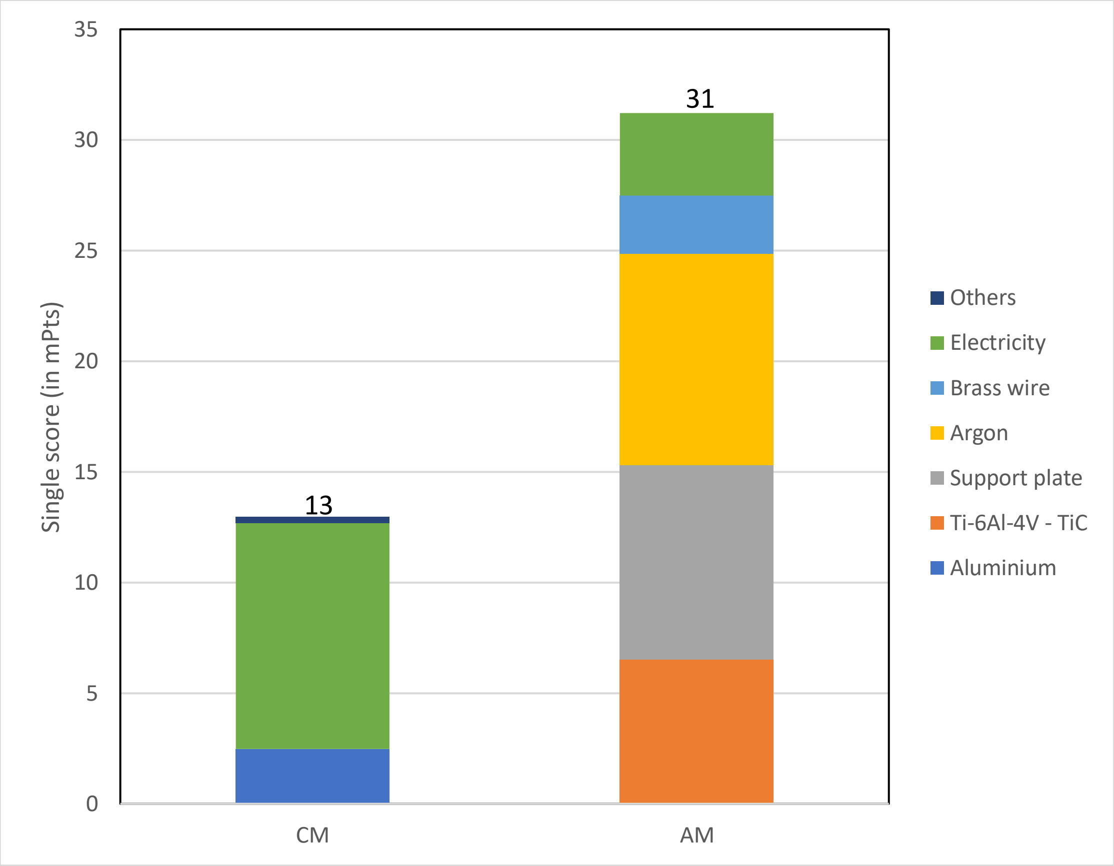

Figure 16. Single score factors for CM (conventional manufacturing) and AM (additive manufacturing) at best scenario values.

5.3.3. Uncertainty results.

Figure 17 shows the discernibility analysis results at single score level for the comparison of CM with AM process, using baseline values, best scenario, with or without weight reduction of 58%. Using the best scenarios, the probability of AM to be less impactful than CM is almost 36% and 43% when weight reduction is considered. These values place them in “about as likely as not” term of the likelihood scale, as used by the IPPC in their Assessment Reports (Mastrandrea et al., 2010), meaning that the probabilistic occurrence is about even. This outcome means that even with the investigated best operating conditions and a 58% weight reduction, the AM technology cannot bring significant environmental benefits, when considering only the production phase. More information about the distribution of uncertainty results from the discernibility analysis is included in Supplementary Material, Tables S9, S10&S11.

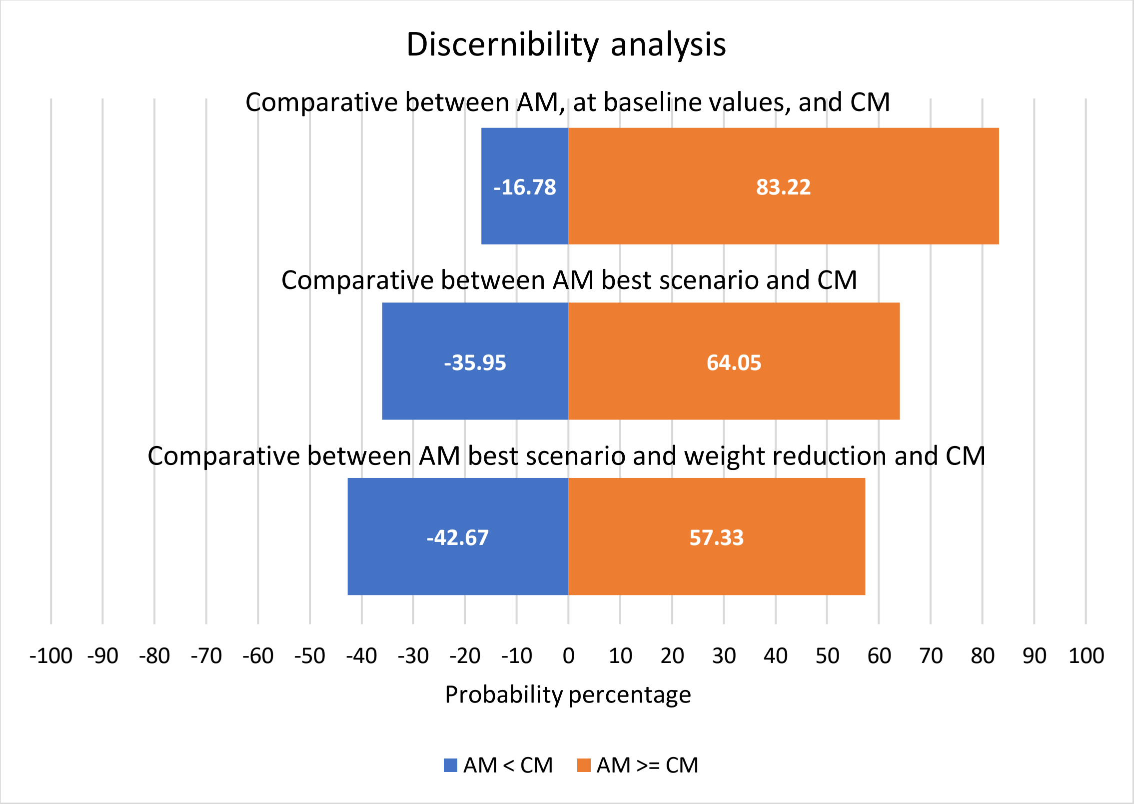

Figure 17. Discernibility analysis between different scenarios for CM (conventional manufacturing) and AM (additive manufacturing) comparative.

5.3.4. Use phase results.

Table 13 is built showing the covered kilometres necessary to equal the CM impact in relation with the weight reduction, as explained in the calculation for Eq. 4. The calculation is based on the best-case AM scenario and at single score level. The results suggest that if the gearbox piece is installed in a car, at least 56% weight reduction is required. Indeed, this is the minimum weight to obtain a quite reasonable range of kilometres, aligned with the standard vehicle lifetime (commonly between 150,000 and 320,000 km) (Kawamoto et al., 2019). This value is slightly lower than the 58% reduction calculated when considering the production phase only. The fuel savings benefits during the gearbox component use are marginal. This is a logical finding, considering the small contribution of the gearbox to the total vehicle weight.

Table 13. Relation between km covered by the AM (additive manufacturing) piece and the weight reduction to equal CM (conventional manufacturing) impact.

Thousands of kilometres covered	Weight reduction
7,717	0%
4,417	25%
1,117	50%
787	52.5%
457	55%
325	56%
259	56.5%
193	57%
127	57.5%
61	58%
0	58.46%

5.4. Discussion.

The findings of this LCA are aligned with those in other studies. For instance, the requirement of mass reduction and design inclusion to reduce impacts from AM compare to a CM technique was also addressed by van Sice & Faludi, (2021). Also, the results from Ingarao et al., (2018) shown that AM is only more sustainable when considering a 50% weight reduction and including the use phase benefits.

The stepwise approach presented in this document can be replicated for similar and different applications within industry field. For this purpose, would be necessary to consider some limitations of the study that could have slightly influenced the results mentioned throughout the paper. Highest extent of produced impacts come from the chosen variables under study, specially from the argon used, as it is shown in the sensitivity analysis. Regarding this issue, no works disclosing quantity and impacts from argon used in DED technology for similar materials were found to date, but some other publications in AM field can help for comparison matters. For instance, while comparing the manufacture of a steel gear (less than 10g) between traditional manufacturing and a directed energy deposition method, Liu et al. (2017) obtained more negative emissions from the latter. They demonstrate a lesser consumption and subsequent environmental impacts from argon than in the present study since the printed item is small and made of steel, therefore the inert printing atmosphere is not as critical as in the titanium case. In a work by Bekker & Verlinden, (2018) performed an LCA on WAMM technique, showing that 48% of impacts comes from the argon gas continuously used in the process. Most of the works that deal with argon utilization are focused on powder metallurgy and gas atomization process to produce diverse material. Peng et al., (2020) shown that argon lead the impacts in the gas atomization process, as is continuously consumed, and has the highest sensitivity among inputs, recommending measures for its reduction. Also, Le et al., (2017) probe that argon is the main environmental impact in the gas atomization process. However, other inputs with relative importance in the outcome were not profoundly assessed. For instance, energy consumption (representing 12% of the single score for the best AM scenario modelled) may change and evolve different in the future, and these variations were only included as uncertainty factor but not with scaled-up values. Regarding this, the results obtained in this study align with those in other works, as in the review performed by Gao et al., (2021), where authors found that machining and conventional techniques have a significant higher energy consumption during manufacturing phase than AM technologies. This study focuses on the key parameters for AM because have more importance in the final outcome, according to the contribution and sensitivity analysis, and considering that their values variation is greater, as shown in the literature review. Along with this, the selection of certain datasets can have an influence in the final outcomes. The database used is the latest available version of ecoinvent during the first half of 2022, and as the process is established in Europe, most of the datasets used are related to the European territory, but for some of them a global average was chosen. In addition, some materials were not found in the database, such as the titanium alloy and the titanium carbide, and are specifically modelled based in other available datasets and literature, as detailed in Supplementary Material, Tables S1&S2. It is also worth mentioning that the datasets used have included an average transport impact, as logistics were not disclosed by the manufacturers involved. Thus, the proposed variables and background system should be subject to review and update, by enhancing the quality of data.

5.5. Conclusion.

This paper followed a stepwise methodology to compare the environmental impacts of emerging technologies with conventional technologies, and to support their eco-design. It was applied to compare an AM technology (Directed Energy Deposition) with a CM casting process, for the production of a gearbox. The outcomes of the study show that the AM technology can only be competitive with the optimization and upscaling of the process design, and with a significant weight reduction of the produced component leading to additional fuel reduction savings during the use phase. The main influencing parameter was found to be the argon recirculation rate. This parameter, as well as the flow rate, deposition and polishing efficiency could be significantly improved based on information from similar technologies. These results can support process developers and manufacturers on the eco-design of the technology and the improvement of the process.

Most studies performed in the AM field do not consider the potential upscaling effects. The use of an ex-ante evaluation based on realistic future scenarios can better support decisions and the technology development trajectory.

The early-stage assessment of emerging technologies is decisive to be able to consider environmental criteria for design choices, while the latter cannot be changed once a higher maturity is achieved. Such ex-ante LCA studies can rely on several approaches, such as hotspot, sensitivity or scenario analysis to prioritize the development strategies and make greener choices, while dealing with the large uncertainties of the modelling for such low technological readiness level. This study could show the applicability of these methods for the specific case of Directed Energy Deposition.

Further research might explore the need for a standardized approach, which allow more reliable comparability between different studies, and the integration with other calculation methods and techniques, such as big data analysis and process simulation tools to further consolidate the LCA modelling.

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5.7. Supplementary information for Chapter 7.

Table S 9. Database sets for the inputs involved in the AM (Additive Manufacturing) technology.

Products	Reference (ecoinvent v3.8 database)
Ti-6Al-4V (support plate)	Ad hoc model created with an average Ti grade V composition, as shown in Santiago-Herrera et al. (2023)
Ti-6Al-4V - TiC	TiC modelled based on SiC and B4C datasets, as shown in Santiago-Herrera et al. (2023)
Argon	Argon, liquid {RER}| market for argon, liquid | APOS, U
Brass wire	Contouring, brass {GLO}| market for | APOS, U
Electricity	Electricity, low voltage {Europe without Switzerland} | market group for | APOS, U

Table S 10. Database sets for the inputs involved in the CM (Conventional Manufacturing) technology.

Products	Reference (ecoinvent v3.8 database)
Aluminium alloy	Aluminium, wrought alloy {GLO}| market for | APOS, U
Water	Water, deionised {Europe without Switzerland} | market for water, deionised | APOS, U
Sand	Silica sand {DE}| production | APOS, U
Oil additive	Lubricating oil {RER}| production | APOS, U
Electricity	Electricity, medium voltage {Europe without Switzerland} | market group for | APOS, U
Wasted water	Wastewater, average {Europe without Switzerland} | market for wastewater, average | APOS, U
Wasted oil	Waste mineral oil {Europe without Switzerland} | market for waste mineral oil | APOS, U
Wasted sand	Waste foundry sand {GLO}| market for waste foundry sand | APOS, U
Wasted aluminium	Waste aluminium {GLO}| market for | APOS, U

Table S 11. Impact factors for CM (Conventional Manufacturing).

Impact category	Unit	Total	Aluminium	Water	Sand	Oil	Electricity	Wasted water	Wasted oil	Wasted sand	Wasted aluminium
Climate change	kg CO2 eq.	1,23E+02	2,58E+01	1,07E-03	3,85E-03	2,60E-01	9,62E+01	1,78E-03	4,86E-01	1,48E-02	3,30E-02
Ozone depletion	kg CFC11 eq.	7,31E-06	1,11E-06	5,81E-10	4,77E-10	1,66E-07	6,02E-06	1,38E-10	7,64E-10	3,12E-09	3,86E-09
Ionising radiation	kBq U-235 eq.	5,68E+01	8,43E-01	1,19E-04	1,93E-04	7,09E-02	5,59E+01	2,39E-04	2,47E-04	1,05E-03	2,76E-03
Photochemical ozone formation	kg NMVOC eq.	3,09E-01	8,49E-02	3,11E-06	2,08E-05	5,65E-03	2,18E-01	8,10E-06	4,59E-05	8,99E-05	1,77E-04
Particulate matter	disease inc.	3,84E-06	2,15E-06	8,24E-11	4,48E-10	1,34E-08	1,67E-06	3,27E-10	1,95E-09	1,62E-09	3,32E-09
Human toxicity, non-cancer	CTUh	1,57E-06	6,29E-07	4,32E-11	4,64E-11	4,65E-09	9,30E-07	3,54E-10	6,07E-10	2,01E-10	7,84E-10
Human toxicity, cancer	CTUh	6,41E-08	3,48E-08	1,15E-12	2,02E-12	1,67E-10	2,90E-08	1,33E-11	4,46E-11	6,47E-12	2,86E-11
Acidification	mol H+ eq.	7,01E-01	1,72E-01	1,00E-05	3,16E-05	1,93E-03	5,26E-01	2,00E-05	4,75E-05	8,15E-05	2,18E-04
Eutrophication, freshwater	kg P eq.	1,07E-01	8,14E-03	3,83E-07	9,15E-07	7,83E-05	9,83E-02	3,99E-06	3,14E-05	1,17E-06	9,21E-06
Eutrophication, marine	kg N eq.	1,22E-01	2,83E-02	9,88E-07	6,76E-06	2,77E-04	9,31E-02	7,33E-05	1,68E-05	2,87E-05	5,59E-05
Eutrophication, terrestrial	mol N eq.	1,10E+00	2,92E-01	9,82E-06	7,45E-05	2,93E-03	7,99E-01	5,69E-05	2,10E-04	3,14E-04	6,01E-04
Ecotoxicity, freshwater	CTUe	2,53E+03	6,84E+02	3,80E+00	7,50E-02	7,88E+00	1,35E+03	1,43E+00	1,76E-01	1,95E-01	4,87E+02
Land use	Pt	4,23E+02	5,73E+01	4,69E-03	1,43E-01	1,79E+00	3,63E+02	2,59E-02	2,59E-02	1,95E-01	5,75E-01
Water use	m3 depriv.	3,45E+01	3,86E+00	1,07E-01	7,01E-03	8,39E-02	3,06E+01	-1,37E-01	6,47E-03	9,08E-04	1,16E-02
Resource use, fossils	MJ	2,33E+03	2,47E+02	1,36E-02	4,54E-02	1,32E+01	2,07E+03	1,98E-02	5,80E-02	2,21E-01	4,70E-01
Resource use, minerals and metals	kg Sb eq.	4,02E-04	1,46E-04	1,50E-08	1,20E-08	3,91E-06	2,51E-04	2,27E-08	3,15E-08	4,59E-08	7,60E-08

Table S 12. Impact factors for AM (Additive Manufacturing) at baseline values.

Impact category	**Unit**	**Total**	**Ti-6Al-4V - TiC**	**Support plate**	**Argon**	**Brass wire**	**Electricity**
Climate change	kg CO2 eq	4,52E+03	1,94E+02	8,61E+01	4,20E+03	2,23E+00	3,69E+01
Ozone depletion	kg CFC11 eq	3,05E-04	2,38E-05	1,08E-05	2,68E-04	2,52E-07	2,34E-06
Ionising radiation	kBq U-235 eq	2,50E+03	1,87E+01	6,23E+00	2,45E+03	3,89E-01	2,13E+01
Photochemical ozone formation	kg NMVOC eq	1,08E+01	7,49E-01	3,38E-01	9,57E+00	1,75E-02	8,66E-02
Particulate matter	disease inc.	9,87E-05	1,57E-05	7,24E-06	7,47E-05	2,62E-07	7,23E-07
Human toxicity, non-cancer	CTUh	4,67E-05	3,01E-06	1,34E-06	4,10E-05	8,76E-07	4,95E-07
Human toxicity, cancer	CTUh	1,89E-06	3,85E-07	1,77E-07	1,30E-06	1,44E-08	1,60E-08
Acidification	mol H+ eq	2,49E+01	1,21E+00	5,29E-01	2,29E+01	7,98E-02	2,13E-01
Eutrophication, freshwater	kg P eq	4,45E+00	1,05E-01	4,47E-02	4,25E+00	5,54E-03	3,79E-02
Eutrophication, marine	kg N eq	4,40E+00	2,00E-01	8,90E-02	4,06E+00	4,88E-03	3,63E-02
Eutrophication, terrestrial	mol N eq	3,83E+01	2,06E+00	9,20E-01	3,50E+01	6,03E-02	3,15E-01
Ecotoxicity, freshwater	CTUe	6,78E+04	5,05E+03	2,28E+03	5,93E+04	5,61E+02	6,00E+02
Land use	Pt	1,75E+04	9,13E+02	4,05E+02	1,59E+04	3,02E+01	1,63E+02
Water use	m3 depriv.	8,16E+03	5,98E+01	2,39E+01	8,06E+03	2,46E+00	1,21E+01
Resource use, fossils	MJ	9,49E+04	2,29E+03	9,73E+02	9,08E+04	3,47E+01	7,90E+02
Resource use, minerals and metals	kg Sb eq	1,51E-02	8,92E-04	3,84E-04	1,19E-02	1,61E-03	3,43E-04

Table S 13. Impact factors for AM (Additive Manufacturing) at best scenario values

Impact category	**Unit**	**Total**	**Ti-6Al-4V - TiC**	**Support plate**	**Argon**	**Brass wire**	**Electricity**
Climate change	kg CO2 eq	2,64E+02	6,35E+01	8,61E+01	8,04E+01	2,23E+00	3,20E+01
Ozone depletion	kg CFC11 eq	2,59E-05	7,77E-06	1,08E-05	5,13E-06	2,52E-07	2,03E-06
Ionising radiation	kBq U-235 eq	7,82E+01	6,13E+00	6,23E+00	4,70E+01	3,89E-01	1,85E+01
Photochemical ozone formation	kg NMVOC eq	8,59E-01	2,45E-01	3,38E-01	1,83E-01	1,75E-02	7,51E-02
Particulate matter	disease inc.	1,47E-05	5,15E-06	7,24E-06	1,43E-06	2,62E-07	6,27E-07
Human toxicity, non-cancer	CTUh	4,42E-06	9,85E-07	1,34E-06	7,86E-07	8,76E-07	4,30E-07
Human toxicity, cancer	CTUh	3,56E-07	1,26E-07	1,77E-07	2,49E-08	1,44E-08	1,39E-08
Acidification	mol H+ eq	1,63E+00	3,95E-01	5,29E-01	4,39E-01	7,98E-02	1,85E-01
Eutrophication, freshwater	kg P eq	1,99E-01	3,43E-02	4,47E-02	8,15E-02	5,54E-03	3,29E-02
Eutrophication, marine	kg N eq	2,69E-01	6,55E-02	8,90E-02	7,79E-02	4,88E-03	3,15E-02
Eutrophication, terrestrial	mol N eq	2,60E+00	6,72E-01	9,20E-01	6,70E-01	6,03E-02	2,74E-01
Ecotoxicity, freshwater	CTUe	6,15E+03	1,65E+03	2,28E+03	1,14E+03	5,61E+02	5,21E+02
Land use	Pt	1,18E+03	2,99E+02	4,05E+02	3,06E+02	3,02E+01	1,42E+02
Water use	m3 depriv.	2,11E+02	1,96E+01	2,39E+01	1,54E+02	2,46E+00	1,05E+01
Resource use, fossils	MJ	4,18E+03	7,49E+02	9,73E+02	1,74E+03	3,47E+01	6,85E+02
Resource use, minerals and metals	kg Sb eq	2,81E-03	2,92E-04	3,84E-04	2,27E-04	1,61E-03	2,97E-04

Table S 14. Single score factors for CM (Conventional Manufacturing).

Impact category	Unit	Total	Aluminium	Water	Sand	Oil	Electricity	Wasted water	Wasted oil	Wasted sand	Wasted aluminium
Total	mPt	1,30E+01	2,47E+00	2,61E-03	4,50E-04	4,74E-02	1,02E+01	4,75E-05	1,40E-02	1,45E-03	2,22E-01
Climate change	mPt	3,19E+00	6,72E-01	2,79E-05	1,00E-04	6,75E-03	2,50E+00	4,64E-05	1,26E-02	3,84E-04	8,59E-04
Ozone depletion	mPt	8,59E-03	1,31E-03	6,83E-07	5,61E-07	1,96E-04	7,08E-03	1,63E-07	8,99E-07	3,67E-06	4,54E-06
Ionising radiation	mPt	6,75E-01	1,00E-02	1,42E-06	2,30E-06	8,42E-04	6,64E-01	2,84E-06	2,93E-06	1,25E-05	3,28E-05
Photochemical ozone formation	mPt	3,64E-01	1,00E-01	3,66E-06	2,45E-05	6,65E-03	2,57E-01	9,54E-06	5,41E-05	1,06E-04	2,08E-04
Particulate matter	mPt	5,78E-01	3,23E-01	1,24E-05	6,74E-05	2,01E-03	2,52E-01	4,93E-05	2,94E-04	2,43E-04	4,99E-04
Human toxicity, non-cancer	mPt	1,25E-01	5,04E-02	3,46E-06	3,72E-06	3,73E-04	7,45E-02	2,83E-05	4,86E-05	1,61E-05	6,28E-05
Human toxicity, cancer	mPt	8,07E-02	4,39E-02	1,45E-06	2,55E-06	2,11E-04	3,65E-02	1,67E-05	5,62E-05	8,16E-06	3,61E-05
Acidification	mPt	7,82E-01	1,92E-01	1,12E-05	3,53E-05	2,16E-03	5,87E-01	2,23E-05	5,31E-05	9,10E-05	2,43E-04
Eutrophication, freshwater	mPt	1,86E+00	1,42E-01	6,68E-06	1,59E-05	1,36E-03	1,71E+00	6,95E-05	5,48E-04	2,03E-05	1,60E-04
Eutrophication, marine	mPt	1,84E-01	4,28E-02	1,50E-06	1,02E-05	4,20E-04	1,41E-01	1,11E-04	2,54E-05	4,35E-05	8,46E-05
Eutrophication, terrestrial	mPt	2,30E-01	6,12E-02	2,06E-06	1,56E-05	6,15E-04	1,68E-01	1,19E-05	4,41E-05	6,60E-05	1,26E-04
Ecotoxicity, freshwater	mPt	1,14E+00	3,08E-01	1,71E-03	3,37E-05	3,55E-03	6,07E-01	6,45E-04	7,92E-05	8,75E-05	2,19E-01
Land use	mPt	4,10E-02	5,55E-03	4,55E-07	1,38E-05	1,73E-04	3,51E-02	2,51E-06	2,51E-06	1,89E-05	5,57E-05
Water use	mPt	2,56E-01	2,87E-02	7,95E-04	5,20E-05	6,23E-04	2,27E-01	-1,02E-03	4,80E-05	6,73E-06	8,61E-05
Resource use, fossils	mPt	2,98E+00	3,17E-01	1,74E-05	5,81E-05	1,68E-02	2,64E+00	2,53E-05	7,42E-05	2,83E-04	6,02E-04
Resource use, minerals and metals	mPt	4,76E-01	1,73E-01	1,78E-05	1,42E-05	4,63E-03	2,98E-01	2,69E-05	3,74E-05	5,44E-05	9,01E-05
Impact category	**Unit**	**Total**	**Aluminium**	**Water**	**Sand**	**Oil**	**Electricity**	**Wasted water**	**Wasted oil**	**Wasted sand**	**Wasted aluminium**
Total	%	100	19,042	0,020	0,003	0,366	78,736	0,000	0,108	0,011	1,713
Climate change	%	100	21,025	0,001	0,003	0,211	78,324	0,001	0,396	0,012	0,027
Ozone depletion	%	100	15,239	0,008	0,007	2,277	82,362	0,002	0,010	0,043	0,053
Ionising radiation	%	100	1,484	0,000	0,000	0,125	98,383	0,000	0,000	0,002	0,005
Photochemical ozone formation	%	100	27,480	0,001	0,007	1,827	70,582	0,003	0,015	0,029	0,057
Particulate matter	%	100	55,855	0,002	0,012	0,348	43,595	0,009	0,051	0,042	0,086
Human toxicity, non-cancer	%	100	40,151	0,003	0,003	0,297	59,422	0,023	0,039	0,013	0,050
Human toxicity, cancer	%	100	54,388	0,002	0,003	0,261	45,201	0,021	0,070	0,010	0,045
Acidification	%	100	24,539	0,001	0,005	0,276	75,127	0,003	0,007	0,012	0,031
Eutrophication, freshwater	%	100	7,641	0,000	0,001	0,073	92,241	0,004	0,030	0,001	0,009
Eutrophication, marine	%	100	23,193	0,001	0,006	0,228	76,430	0,060	0,014	0,024	0,046
Eutrophication, terrestrial	%	100	26,637	0,001	0,007	0,268	72,980	0,005	0,019	0,029	0,055
Ecotoxicity, freshwater	%	100	27,005	0,150	0,003	0,311	53,239	0,057	0,007	0,008	19,221
Land use	%	100	13,560	0,001	0,034	0,423	85,787	0,006	0,006	0,046	0,136
Water use	%	100	11,186	0,310	0,020	0,243	88,583	-0,398	0,019	0,003	0,034
Resource use, fossils	%	100	10,627	0,001	0,002	0,566	88,772	0,001	0,002	0,010	0,020
Resource use, minerals and metals	%	100	36,401	0,004	0,003	0,973	62,575	0,006	0,008	0,011	0,019

Table S 15. Single score factors for AM (Additive Manufacturing) at baseline values.

Impact category	**Unit**	**Total**	**Ti-6Al-4V - TiC**	**Support plate**	**Argon**	**Brass wire**	**Electricity**
Total	mPt	5,33E+02	2,00E+01	8,78E+00	4,98E+02	2,64E+00	4,30E+00
Climate change	mPt	1,17E+02	5,05E+00	2,24E+00	1,09E+02	5,81E-02	9,60E-01
Ozone depletion	mPt	3,58E-01	2,79E-02	1,27E-02	3,15E-01	2,97E-04	2,75E-03
Ionising radiation	mPt	2,97E+01	2,23E-01	7,40E-02	2,91E+01	4,62E-03	2,53E-01
Photochemical ozone formation	mPt	1,27E+01	8,81E-01	3,98E-01	1,13E+01	2,06E-02	1,02E-01
Particulate matter	mPt	1,49E+01	2,37E+00	1,09E+00	1,12E+01	3,94E-02	1,09E-01
Human toxicity, non-cancer	mPt	3,74E+00	2,41E-01	1,08E-01	3,28E+00	7,02E-02	3,97E-02
Human toxicity, cancer	mPt	2,39E+00	4,85E-01	2,23E-01	1,64E+00	1,82E-02	2,01E-02
Acidification	mPt	2,78E+01	1,35E+00	5,90E-01	2,56E+01	8,90E-02	2,37E-01
Eutrophication, freshwater	mPt	7,75E+01	1,83E+00	7,78E-01	7,41E+01	9,65E-02	6,60E-01
Eutrophication, marine	mPt	6,66E+00	3,03E-01	1,35E-01	6,16E+00	7,38E-03	5,50E-02
Eutrophication, terrestrial	mPt	8,04E+00	4,31E-01	1,93E-01	7,34E+00	1,27E-02	6,62E-02
Ecotoxicity, freshwater	mPt	3,05E+01	2,27E+00	1,03E+00	2,67E+01	2,52E-01	2,70E-01
Land use	mPt	1,69E+00	8,85E-02	3,92E-02	1,54E+00	2,93E-03	1,58E-02
Water use	mPt	6,05E+01	4,44E-01	1,78E-01	5,98E+01	1,83E-02	8,98E-02
Resource use, fossils	mPt	1,21E+02	2,93E+00	1,24E+00	1,16E+02	4,44E-02	1,01E+00
Resource use, minerals and metals	mPt	1,79E+01	1,06E+00	4,55E-01	1,41E+01	1,91E+00	4,07E-01
Impact category	**Unit**	**Total**	**Ti-6Al-4V - TiC**	**Support plate**	**Argon**	**Brass wire**	**Electricity**
Total	%	100	3,749	1,647	93,303	0,495	0,806
Climate change	%	100	4,301	1,906	92,926	0,049	0,817
Ozone depletion	%	100	7,798	3,531	87,821	0,083	0,767
Ionising radiation	%	100	0,750	0,249	98,133	0,016	0,852
Photochemical ozone formation	%	100	6,959	3,144	88,930	0,163	0,805
Particulate matter	%	100	15,959	7,339	75,704	0,265	0,732
Human toxicity, non-cancer	%	100	6,449	2,874	87,741	1,876	1,060
Human toxicity, cancer	%	100	20,332	9,339	68,725	0,761	0,843
Acidification	%	100	4,845	2,121	91,861	0,320	0,853
Eutrophication, freshwater	%	100	2,363	1,005	95,656	0,125	0,852
Eutrophication, marine	%	100	4,558	2,024	92,481	0,111	0,826
Eutrophication, terrestrial	%	100	5,364	2,402	91,254	0,157	0,823
Ecotoxicity, freshwater	%	100	7,442	3,363	87,484	0,827	0,885
Land use	%	100	5,232	2,319	91,340	0,173	0,936
Water use	%	100	0,734	0,293	98,794	0,030	0,148
Resource use, fossils	%	100	2,414	1,025	95,692	0,037	0,832
Resource use, minerals and metals	%	100	5,915	2,544	78,613	10,656	2,272

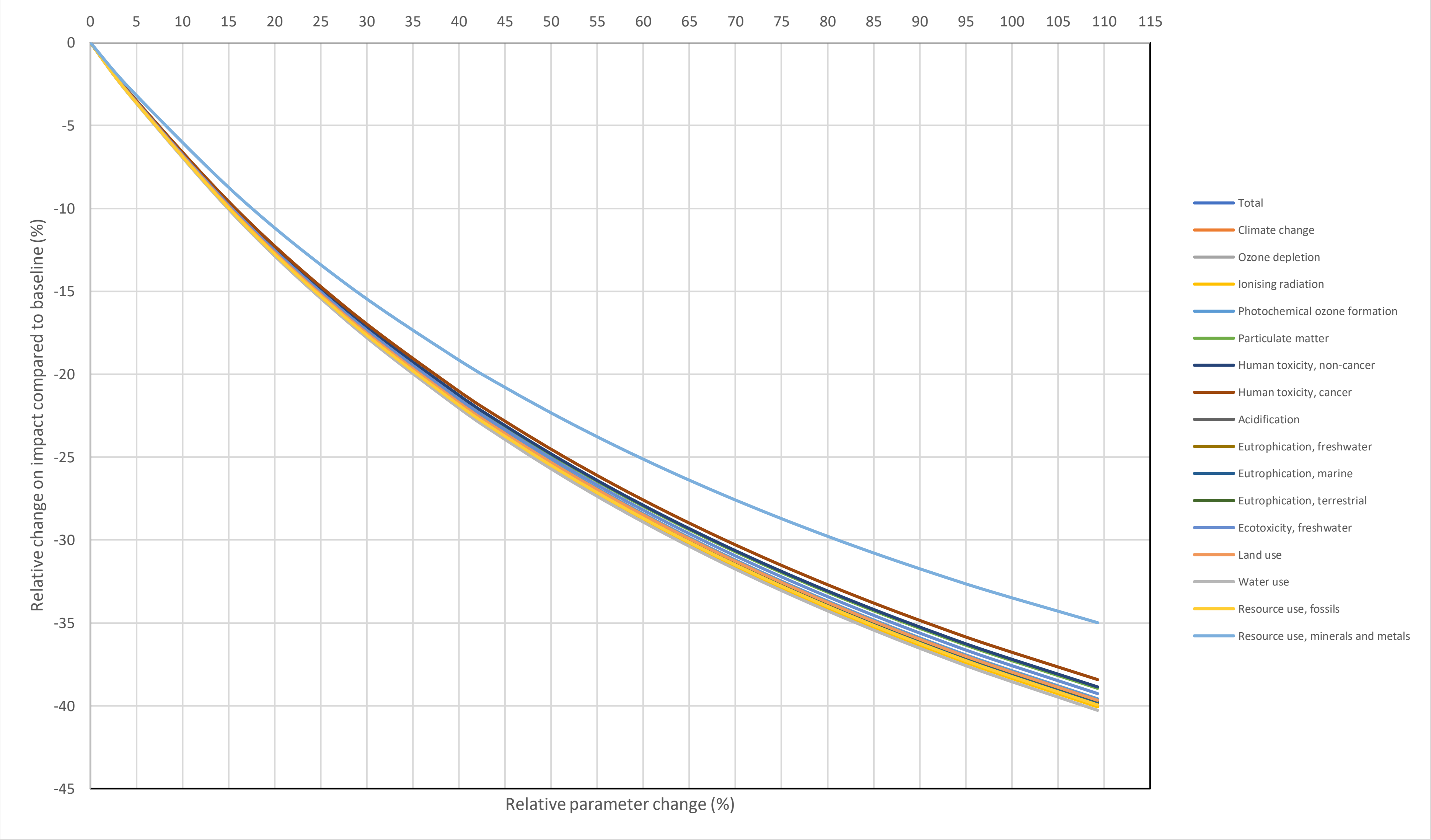

Figure S 1. Baseline value variation and relative result score, in percentage, for $\eta_{Deposition}$.

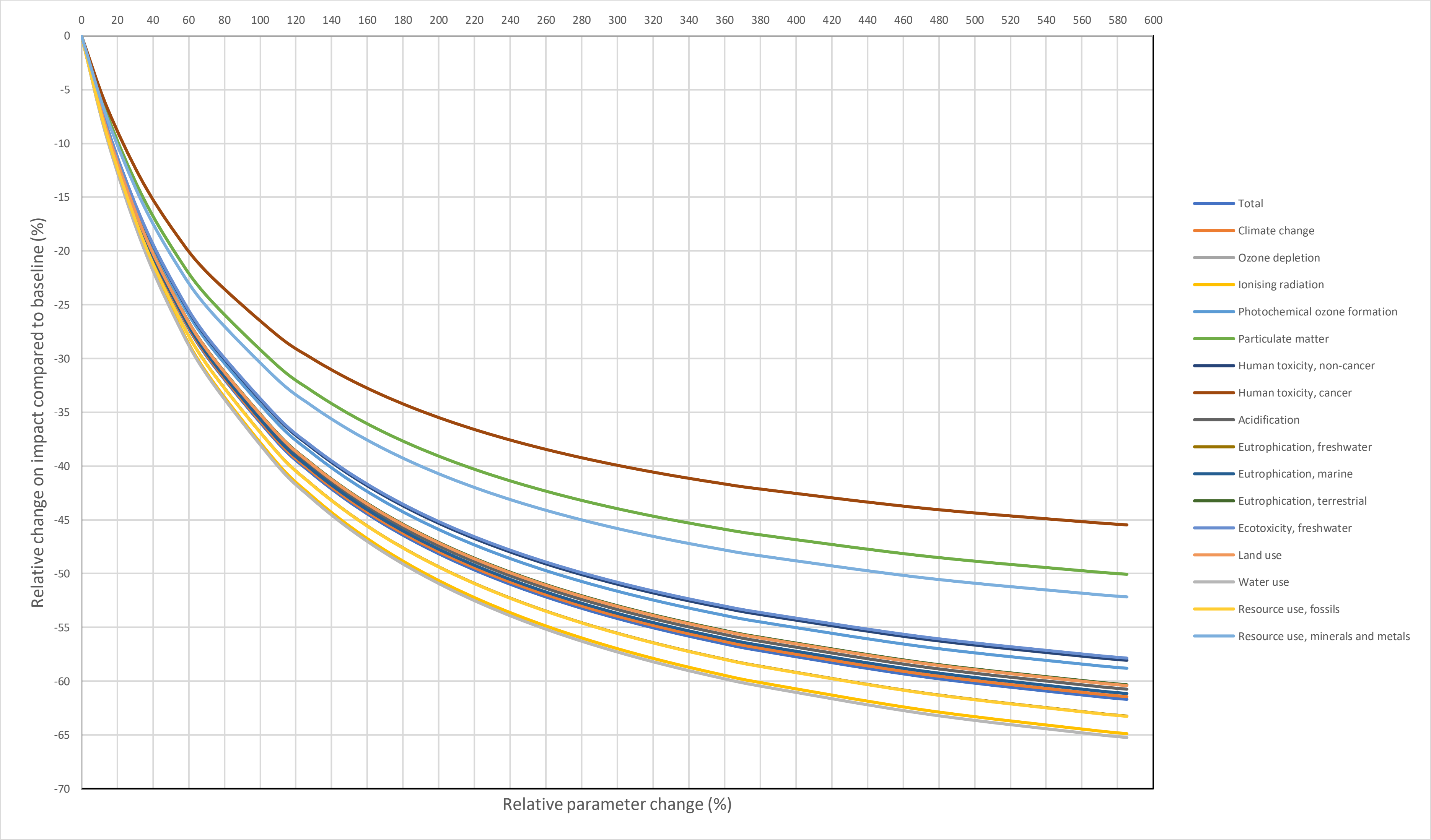

Figure S 2. Baseline value variation and relative result score, in percentage, for r_{Flow}.

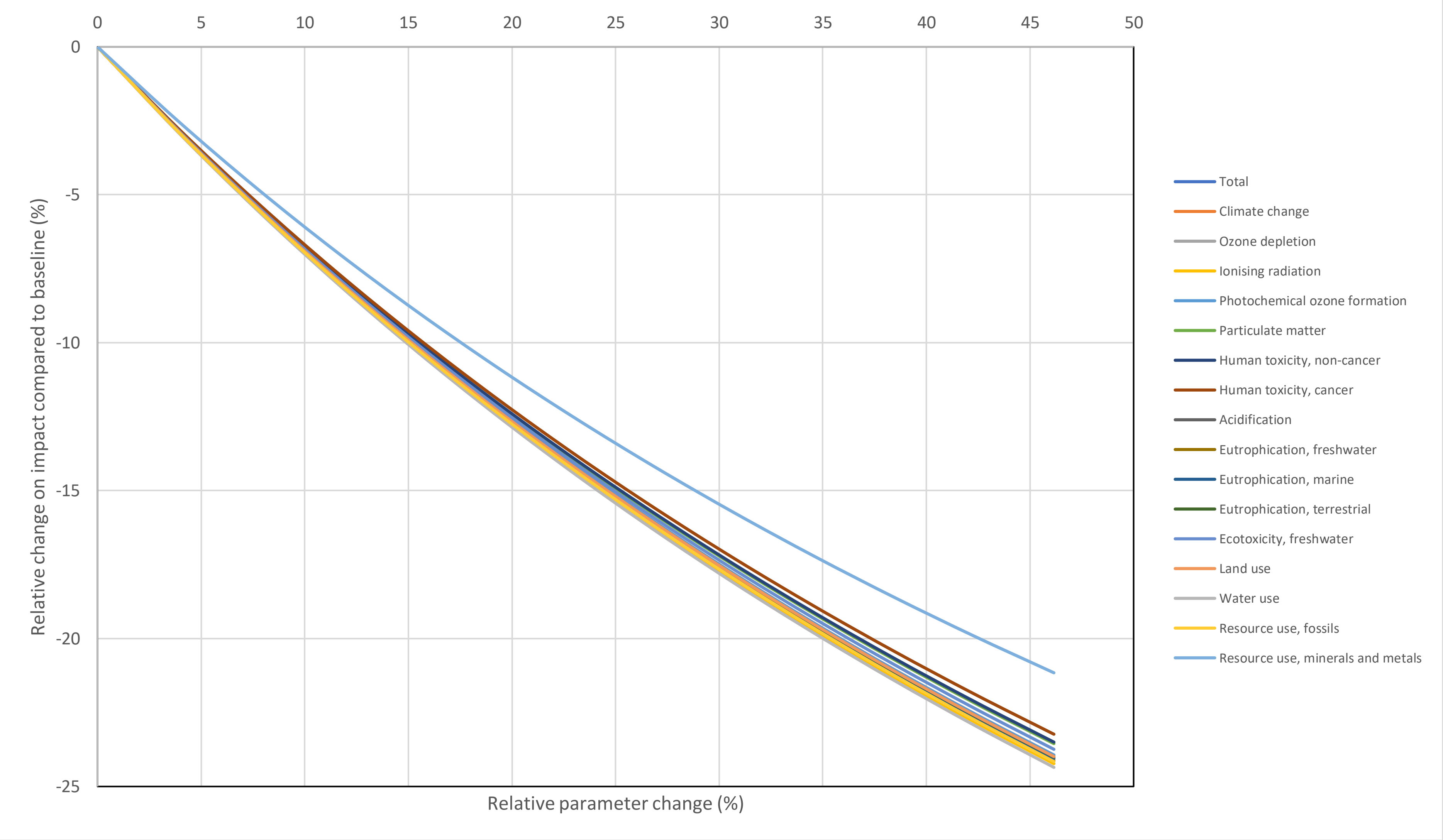

Figure S 3. Baseline value variation and relative result score, in percentage, for $\eta_{Polishing}$.

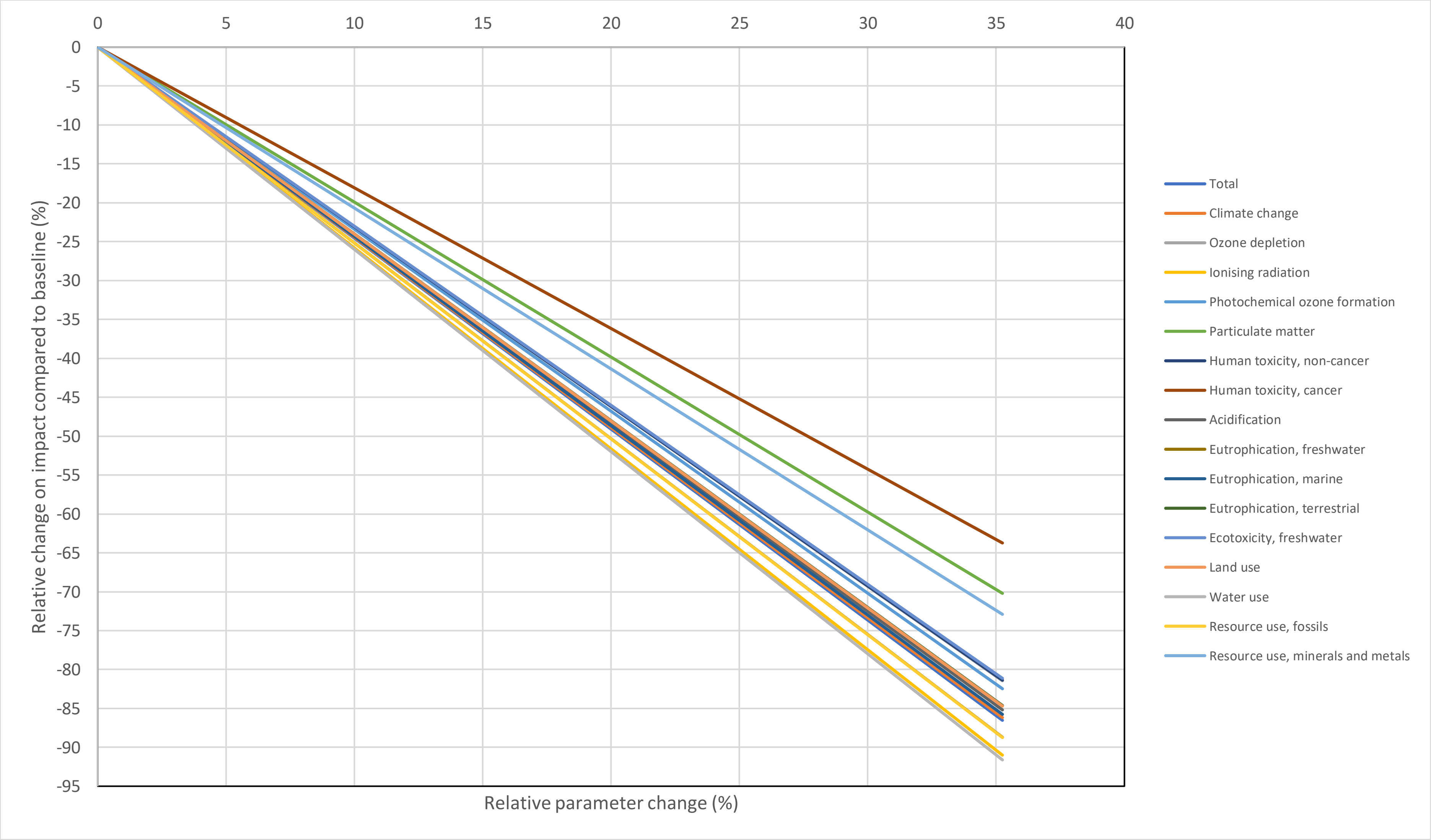

Figure S 4. Baseline value variation and relative result score, in percentage, for $r_{Recirculation}$.

Table S 16. Single score factors for AM (Additive Manufacturing) at best scenario values.

Impact category	**Unit**	**Total**	**Ti-6Al-4V - TiC**	**Support plate**	**Argon**	**Brass wire**	**Electricity**
Total	mPt	3,12E+01	6,53E+00	8,78E+00	9,53E+00	2,64E+00	3,73E+00
Climate change	mPt	6,87E+00	1,65E+00	2,24E+00	2,09E+00	5,81E-02	8,33E-01
Ozone depletion	mPt	3,05E-02	9,14E-03	1,27E-02	6,03E-03	2,97E-04	2,39E-03
Ionising radiation	mPt	9,29E-01	7,27E-02	7,40E-02	5,58E-01	4,62E-03	2,19E-01
Photochemical ozone formation	mPt	1,01E+00	2,88E-01	3,98E-01	2,16E-01	2,06E-02	8,84E-02
Particulate matter	mPt	2,21E+00	7,75E-01	1,09E+00	2,16E-01	3,94E-02	9,44E-02
Human toxicity, non-cancer	mPt	3,54E-01	7,89E-02	1,08E-01	6,29E-02	7,02E-02	3,44E-02
Human toxicity, cancer	mPt	4,48E-01	1,59E-01	2,23E-01	3,14E-02	1,82E-02	1,75E-02
Acidification	mPt	1,82E+00	4,41E-01	5,90E-01	4,90E-01	8,90E-02	2,06E-01
Eutrophication, freshwater	mPt	3,47E+00	5,98E-01	7,78E-01	1,42E+00	9,65E-02	5,73E-01
Eutrophication, marine	mPt	4,07E-01	9,92E-02	1,35E-01	1,18E-01	7,38E-03	4,77E-02
Eutrophication, terrestrial	mPt	5,45E-01	1,41E-01	1,93E-01	1,41E-01	1,27E-02	5,74E-02
Ecotoxicity, freshwater	mPt	2,77E+00	7,42E-01	1,03E+00	5,12E-01	2,52E-01	2,34E-01
Land use	mPt	1,14E-01	2,89E-02	3,92E-02	2,96E-02	2,93E-03	1,37E-02
Water use	mPt	1,56E+00	1,45E-01	1,78E-01	1,15E+00	1,83E-02	7,79E-02
Resource use, fossils	mPt	5,35E+00	9,59E-01	1,24E+00	2,23E+00	4,44E-02	8,77E-01
Resource use, minerals and metals	mPt	3,33E+00	3,46E-01	4,55E-01	2,70E-01	1,91E+00	3,53E-01
Impact category	**Unit**	**Total**	**Ti-6Al-4V - TiC**	**Support plate**	**Argon**	**Brass wire**	**Electricity**
Total	%	100	20,928	28,132	30,538	8,460	11,942
Climate change	%	100	24,029	32,574	30,434	0,845	12,118
Ozone depletion	%	100	29,948	41,481	19,774	0,973	7,824
Ionising radiation	%	100	7,831	7,968	60,083	0,498	23,620
Photochemical ozone formation	%	100	28,492	39,378	21,346	2,040	8,744
Particulate matter	%	100	34,996	49,229	9,732	1,779	4,263
Human toxicity, non-cancer	%	100	22,288	30,382	17,777	19,828	9,725
Human toxicity, cancer	%	100	35,362	49,686	7,008	4,051	3,893
Acidification	%	100	24,275	32,504	26,980	4,901	11,340
Eutrophication, freshwater	%	100	17,262	22,454	40,976	2,785	16,523
Eutrophication, marine	%	100	24,368	33,103	28,989	1,814	11,726
Eutrophication, terrestrial	%	100	25,880	35,445	25,812	2,324	10,539
Ecotoxicity, freshwater	%	100	26,833	37,091	18,493	9,117	8,466
Land use	%	100	25,283	34,276	25,876	2,560	12,005
Water use	%	100	9,275	11,348	73,229	1,166	4,981
Resource use, fossils	%	100	17,909	23,257	41,618	0,830	16,385
Resource use, minerals and metals	%	100	10,390	13,667	8,095	57,254	10,594

Table S 17. Discernibility analysis comparative factors between AM, at baseline values, and CM.

Discernibility analysis comparative factors between AM, at baseline values, and CM								
Characterisation (Confidence interval: 95)								
Impact category	**A >= B**	**Mean**	**Median**	**SD**	**CV**	**2,50%**	**97,50%**	**SEM**
Climate change	99,2	4,62E+03	4,52E+03	2,00E+03	4,33E+01	9,64E+02	8,88E+03	2,00E+01
Ozone depletion	99,4	3,13E-04	3,03E-04	1,35E-04	4,32E+01	7,78E-05	6,14E-04	1,35E-06
Ionising radiation	99,02	2,55E+03	1,73E+03	3,26E+03	1,28E+02	2,87E+02	9,99E+03	3,26E+01
Photochemical ozone formation	99,34	1,10E+01	1,07E+01	4,61E+00	4,20E+01	2,62E+00	2,09E+01	4,61E-02
Particulate matter	99,71	9,92E-05	9,61E-05	3,94E-05	3,97E+01	3,05E-05	1,86E-04	3,94E-07
Human toxicity, non-cancer	50,93	5,12E-05	1,56E-05	1,41E-03	2,76E+03	-2,86E-03	2,97E-03	1,41E-05
Human toxicity, cancer	57,52	1,94E-06	1,42E-06	1,20E-05	6,16E+02	-2,25E-05	2,72E-05	1,20E-07
Acidification	99,24	2,55E+01	2,50E+01	1,09E+01	4,30E+01	5,55E+00	4,88E+01	1,09E-01
Eutrophication, freshwater	99,17	4,58E+00	3,66E+00	3,75E+00	8,18E+01	5,96E-01	1,38E+01	3,75E-02
Eutrophication, marine	99,23	4,49E+00	4,37E+00	1,95E+00	4,34E+01	9,43E-01	8,64E+00	1,95E-02
Eutrophication, terrestrial	99,26	3,91E+01	3,81E+01	1,68E+01	4,30E+01	8,59E+00	7,50E+01	1,68E-01
Ecotoxicity, freshwater	99,36	6,84E+04	6,57E+04	3,09E+04	4,51E+01	1,60E+04	1,37E+05	3,09E+02
Land use	99,29	1,79E+04	1,73E+04	7,96E+03	4,45E+01	3,92E+03	3,50E+04	7,96E+01
Water use	56,7	8,50E+03	9,00E+03	8,08E+04	9,50E+02	-1,66E+05	1,70E+05	8,08E+02
Resource use, fossils	99,13	9,71E+04	9,35E+04	4,49E+04	4,63E+01	1,83E+04	1,98E+05	4,49E+02
Resource use, minerals and metals	99,71	1,53E-02	1,50E-02	5,86E-03	3,82E+01	4,82E-03	2,80E-02	5,86E-05
Weighting (Confidence interval: 95)								
Impact category	**A >= B**	**Mean**	**Median**	**SD**	**CV**	**2,50%**	**97,50%**	**SEM**
Climate change	99,2	1,20E-01	1,18E-01	5,20E-02	4,33E+01	2,51E-02	2,31E-01	5,20E-04
Ozone depletion	99,4	3,68E-04	3,56E-04	1,59E-04	4,32E+01	9,15E-05	7,22E-04	1,59E-06
Ionising radiation	99,02	3,03E-02	2,05E-02	3,87E-02	1,28E+02	3,41E-03	1,19E-01	3,87E-04
Photochemical ozone formation	99,34	1,29E-02	1,26E-02	5,43E-03	4,20E+01	3,08E-03	2,46E-02	5,43E-05
Particulate matter	99,71	1,49E-02	1,45E-02	5,93E-03	3,97E+01	4,59E-03	2,80E-02	5,93E-05
Human toxicity, non-cancer	50,93	4,10E-03	1,25E-03	1,13E-01	2,76E+03	-2,29E-01	2,38E-01	1,13E-03
Human toxicity, cancer	57,52	2,45E-03	1,79E-03	1,51E-02	6,16E+02	-2,84E-02	3,43E-02	1,51E-04
Acidification	99,24	2,84E-02	2,79E-02	1,22E-02	4,30E+01	6,19E-03	5,45E-02	1,22E-04
Eutrophication, freshwater	99,17	7,98E-02	6,37E-02	6,53E-02	8,18E+01	1,04E-02	2,41E-01	6,53E-04
Eutrophication, marine	99,23	6,80E-03	6,62E-03	2,95E-03	4,34E+01	1,43E-03	1,31E-02	2,95E-05
Eutrophication, terrestrial	99,26	8,20E-03	8,00E-03	3,52E-03	4,30E+01	1,80E-03	1,57E-02	3,52E-05
Ecotoxicity, freshwater	99,36	3,08E-02	2,95E-02	1,39E-02	4,51E+01	7,22E-03	6,16E-02	1,39E-04
Land use	99,29	1,73E-03	1,67E-03	7,72E-04	4,45E+01	3,80E-04	3,39E-03	7,72E-06
Water use	56,7	6,31E-02	6,68E-02	5,99E-01	9,50E+02	-1,23E+00	1,26E+00	5,99E-03
Resource use, fossils	99,13	1,24E-01	1,20E-01	5,75E-02	4,63E+01	2,34E-02	2,53E-01	5,75E-04
Resource use, minerals and metals	99,71	1,82E-02	1,78E-02	6,95E-03	3,82E+01	5,71E-03	3,32E-02	6,95E-05
Single score (Confidence interval: 95)								
Impact category	**AM >= CM**	**Mean**	**Median**	**SD**	**CV**	**2,50%**	**97,50%**	**SEM**
Single score	83,22	5,46E-01	4,78E-01	6,63E-01	1,21E+02	-6,61E-01	2,04E+00	6,63E-03

Table S 18. Discernibility analysis comparative factors between AM best scenario and CM.

Discernibility analysis comparative factors between AM best scenario and CM								
Characterisation (Confidence interval: 95)								
Impact category	**A >= B**	**Mean**	**Median**	**SD**	**CV**	**2,50%**	**97,50%**	**SEM**
Climate change	62,22	1,38E+02	1,74E+02	5,82E+02	4,21E+02	-1,11E+03	1,17E+03	5,82E+00
Ozone depletion	70,43	1,85E-05	2,08E-05	3,82E-05	2,06E+02	-6,18E-05	8,75E-05	3,82E-07
Ionising radiation	55,37	2,62E+01	2,82E+01	4,79E+02	1,83E+03	-8,29E+02	8,77E+02	4,79E+00
Photochemical ozone formation	67,88	5,45E-01	6,33E-01	1,35E+00	2,47E+02	-2,30E+00	2,95E+00	1,35E-02
Particulate matter	82,95	1,09E-05	1,11E-05	1,18E-05	1,08E+02	-1,26E-05	3,39E-05	1,18E-07
Human toxicity, non-cancer	52,54	1,42E-06	2,27E-06	1,64E-04	1,16E+04	-3,57E-04	3,53E-04	1,64E-06
Human toxicity, cancer	66,23	2,84E-07	2,64E-07	1,41E-06	4,97E+02	-2,81E-06	3,35E-06	1,41E-08
Acidification	63,9	9,12E-01	1,12E+00	3,19E+00	3,49E+02	-5,90E+00	6,58E+00	3,19E-02
Eutrophication, freshwater	60,15	8,82E-02	1,04E-01	6,99E-01	7,92E+02	-1,41E+00	1,43E+00	6,99E-03
Eutrophication, marine	62,8	1,44E-01	1,81E-01	5,65E-01	3,92E+02	-1,06E+00	1,15E+00	5,65E-03
Eutrophication, terrestrial	64,51	1,48E+00	1,80E+00	4,88E+00	3,30E+02	-8,96E+00	1,02E+01	4,88E-02
Ecotoxicity, freshwater	68,85	3,60E+03	4,02E+03	8,55E+03	2,38E+02	-1,42E+04	1,93E+04	8,55E+01
Land use	65,98	7,51E+02	8,83E+02	2,24E+03	2,98E+02	-3,99E+03	4,79E+03	2,24E+01
Water use	51,47	2,02E+02	1,53E+02	1,00E+04	4,94E+03	-2,16E+04	2,13E+04	1,00E+02
Resource use, fossils	58,91	1,76E+03	2,50E+03	1,27E+04	7,20E+02	-2,50E+04	2,44E+04	1,27E+02
Resource use, minerals and metals	91,13	2,40E-03	2,48E-03	1,77E-03	7,36E+01	-1,27E-03	5,72E-03	1,77E-05
Weighting (Confidence interval: 95)								
Impact category	**A >= B**	**Mean**	**Median**	**SD**	**CV**	**2,50%**	**97,50%**	**SEM**
Climate change	62,22	3,60E-03	4,53E-03	1,51E-02	4,21E+02	-2,88E-02	3,04E-02	1,51E-04
Ozone depletion	70,43	2,18E-05	2,45E-05	4,49E-05	2,06E+02	-7,27E-05	1,03E-04	4,49E-07
Ionising radiation	55,37	3,12E-04	3,35E-04	5,69E-03	1,83E+03	-9,84E-03	1,04E-02	5,69E-05
Photochemical ozone formation	67,88	6,42E-04	7,46E-04	1,59E-03	2,47E+02	-2,71E-03	3,48E-03	1,59E-05
Particulate matter	82,95	1,64E-03	1,67E-03	1,78E-03	1,08E+02	-1,90E-03	5,10E-03	1,78E-05
Human toxicity, non-cancer	52,54	1,14E-04	1,82E-04	1,31E-02	1,16E+04	-2,86E-02	2,83E-02	1,31E-04
Human toxicity, cancer	66,23	3,58E-04	3,33E-04	1,78E-03	4,97E+02	-3,55E-03	4,23E-03	1,78E-05
Acidification	63,9	1,02E-03	1,25E-03	3,56E-03	3,49E+02	-6,59E-03	7,35E-03	3,56E-05
Eutrophication, freshwater	60,15	1,54E-03	1,81E-03	1,22E-02	7,92E+02	-2,45E-02	2,48E-02	1,22E-04
Eutrophication, marine	62,8	2,19E-04	2,74E-04	8,56E-04	3,92E+02	-1,61E-03	1,74E-03	8,56E-06
Eutrophication, terrestrial	64,51	3,11E-04	3,78E-04	1,02E-03	3,30E+02	-1,88E-03	2,13E-03	1,02E-05
Ecotoxicity, freshwater	68,85	1,62E-03	1,81E-03	3,84E-03	2,38E+02	-6,37E-03	8,70E-03	3,84E-05
Land use	65,98	7,27E-05	8,56E-05	2,17E-04	2,98E+02	-3,87E-04	4,64E-04	2,17E-06
Water use	51,47	1,50E-03	1,14E-03	7,42E-02	4,94E+03	-1,60E-01	1,58E-01	7,42E-04
Resource use, fossils	58,91	2,25E-03	3,20E-03	1,62E-02	7,20E+02	-3,20E-02	3,12E-02	1,62E-04
Resource use, minerals and metals	91,13	2,85E-03	2,94E-03	2,10E-03	7,36E+01	-1,51E-03	6,79E-03	2,10E-05
Single score (Confidence interval: 95)								
Impact category	**AM >= CM**	**Mean**	**Median**	**SD**	**CV**	**2,50%**	**97,50%**	**SEM**
Single score	64,05	1,81E-02	1,66E-02	1,02E-01	5,66E+02	-2,10E-01	2,33E-01	1,02E-03

Table S 19. Discernibility analysis comparative factors between AM best scenario and weight reduction and CM.

Discernibility analysis comparative factors between AM best scenario and weight reduction and CM								
Characterisation (Confidence interval: 95)								
Impact category	**A >= B**	**Mean**	**Median**	**SD**	**CV**	**2,50%**	**97,50%**	**SEM**
Climate change	50,26	-1,31E+01	2,08E+00	2,39E+02	-1,82E+03	-5,25E+02	4,07E+02	2,39E+00
Ozone depletion	61,66	3,53E-06	4,51E-06	1,56E-05	4,41E+02	-3,04E-05	3,15E-05	1,56E-07
Ionising radiation	45,79	-2,32E+01	-1,04E+01	1,97E+02	-8,50E+02	-4,21E+02	2,80E+02	1,97E+00
Photochemical ozone formation	55,95	4,92E-02	8,23E-02	5,50E-01	1,12E+03	-1,13E+00	1,02E+00	5,50E-03
Particulate matter	70,64	2,32E-06	2,41E-06	4,73E-06	2,04E+02	-7,35E-06	1,13E-05	4,73E-08
Human toxicity, non-cancer	52,27	-6,15E-08	8,95E-07	7,04E-05	-1,14E+05	-1,56E-04	1,51E-04	7,04E-07
Human toxicity, cancer	64,71	8,26E-08	9,51E-08	6,06E-07	7,33E+02	-1,29E-06	1,34E-06	6,06E-09
Acidification	51,53	-2,46E-02	6,07E-02	1,31E+00	-5,31E+03	-2,83E+00	2,28E+00	1,31E-02
Eutrophication, freshwater	49,47	-2,50E-02	-2,89E-03	2,92E-01	-1,17E+03	-6,61E-01	4,93E-01	2,92E-03
Eutrophication, marine	50,59	-1,02E-02	4,32E-03	2,32E-01	-2,28E+03	-5,08E-01	3,99E-01	2,32E-03
Eutrophication, terrestrial	51,96	-1,50E-02	1,08E-01	2,00E+00	-1,34E+04	-4,29E+00	3,52E+00	2,00E-02
Ecotoxicity, freshwater	52,36	1,03E+01	2,09E+02	3,50E+03	3,39E+04	-7,59E+03	6,29E+03	3,50E+01
Land use	55,53	6,70E+01	1,30E+02	9,14E+02	1,36E+03	-1,93E+03	1,69E+03	9,14E+00
Water use	52,6	2,74E+01	1,00E+02	4,02E+03	1,47E+04	-8,95E+03	8,50E+03	4,02E+01
Resource use, fossils	48,05	-6,04E+02	-2,65E+02	5,20E+03	-8,61E+02	-1,19E+04	8,65E+03	5,20E+01
Resource use, minerals and metals	86,29	7,69E-04	7,99E-04	7,23E-04	9,40E+01	-7,45E-04	2,11E-03	7,23E-06
Weighting (Confidence interval: 95)								
Impact category	**A >= B**	**Mean**	**Median**	**SD**	**CV**	**2,50%**	**97,50%**	**SEM**
Climate change	50,26	-3,41E-04	5,40E-05	6,22E-03	-1,82E+03	-1,37E-02	1,06E-02	6,22E-05
Ozone depletion	61,66	4,16E-06	5,30E-06	1,83E-05	4,41E+02	-3,57E-05	3,70E-05	1,83E-07
Ionising radiation	45,79	-2,75E-04	-1,24E-04	2,34E-03	-8,50E+02	-5,00E-03	3,33E-03	2,34E-05
Photochemical ozone formation	55,95	5,79E-05	9,69E-05	6,48E-04	1,12E+03	-1,33E-03	1,21E-03	6,48E-06
Particulate matter	70,64	3,49E-04	3,63E-04	7,12E-04	2,04E+02	-1,11E-03	1,70E-03	7,12E-06
Human toxicity, non-cancer	52,27	-4,93E-06	7,17E-05	5,64E-03	-1,14E+05	-1,25E-02	1,21E-02	5,64E-05
Human toxicity, cancer	64,71	1,04E-04	1,20E-04	7,63E-04	7,33E+02	-1,62E-03	1,69E-03	7,63E-06
Acidification	51,53	-2,74E-05	6,78E-05	1,46E-03	-5,31E+03	-3,16E-03	2,54E-03	1,46E-05
Eutrophication, freshwater	49,47	-4,35E-04	-5,03E-05	5,09E-03	-1,17E+03	-1,15E-02	8,59E-03	5,09E-05
Eutrophication, marine	50,59	-1,54E-05	6,54E-06	3,51E-04	-2,28E+03	-7,70E-04	6,04E-04	3,51E-06
Eutrophication, terrestrial	51,96	-3,14E-06	2,27E-05	4,19E-04	-1,34E+04	-9,00E-04	7,39E-04	4,19E-06
Ecotoxicity, freshwater	52,36	4,64E-06	9,42E-05	1,57E-03	3,39E+04	-3,41E-03	2,83E-03	1,57E-05
Land use	55,53	6,49E-06	1,26E-05	8,85E-05	1,36E+03	-1,87E-04	1,63E-04	8,85E-07
Water use	52,60	2,03E-04	7,46E-04	2,99E-02	1,47E+04	-6,64E-02	6,30E-02	2,99E-04
Resource use, fossils	48,05	-7,73E-04	-3,39E-04	6,66E-03	-8,61E+02	-1,52E-02	1,11E-02	6,66E-05
Resource use, minerals and metals	86,29	9,12E-04	9,47E-04	8,57E-04	9,40E+01	-8,83E-04	2,50E-03	8,57E-06
Single score (Confidence interval: 95)								
Impact category	**AM >= CM**	**Mean**	**Median**	**SD**	**CV**	**2,50%**	**97,50%**	**SEM**
Single score	57,33	-2,34E-04	3,56E-03	4,21E-02	-1,80E+04	-1,03E-01	8,05E-02	4,21E-04

6. General conclusions and final remarks.

Despite sharing a common methodological framework and being connected by a chained production process, each of the works that make up this thesis has its unique findings, that are featured in each publication.

The first work helped to set up the LCA methodology and learn with the practice. Thanks to this, the methodology concepts, the meaning and importance of the environmental impact categories, and especially, the whole iterative process of data collection and its subsequent processing through the environmental calculation software, were understood and internalised, thus helping to generate a higher scientific quality in the rest of publications. The importance of this study lies in the fact that it was the first attempt found in literature for a complete comparative analysis of the two different manufacturing techniques, and especially with such a specific material as an aluminium metal matrix composite reinforced with TiO2 particles. It shows that the main environmental hotspots in this kind of technologies are related with the material used and the energy dependency. In this case, the difference in environmental impacts between the two technologies is not relevant, making it necessary to implement an economic analysis, thus assisting in the selection of a technology as the most appropriate.

The second work, that compares the production of titanium powder from two different technologies suitable to feed Additive Manufacturing systems, is the first to date in its field related with MMCs, and that start with raw material instead of scraps from other processes. In fact, the powders are relatively different because one is pure titanium alloy, and the second technology is able to produce a titanium composite reinforced with TiC particles. It is proven that the alternative manufacturing process is much more environmentally clean than its counterpart, which is highly affected by the intensive use of argon gas. As some of the processes and materials involved were not included in databases, some *ad hoc* models were created to perform a complete assessment, generating information from other datasets and literature findings. This was a step forward in the progress of the research thesis and knowledge generation in the field, resulting also in new data that can be used in future research. In addition, the material produced and assessed is the basis for the next study, so this work is of particular importance for the final resolution of the thesis.

The third study compares a traditional and an emerging technology to manufacture a metallic gearbox. To perform this in a fair way, since both technologies are at different mature level, a complex parametrized prospective approach model is created to scaled up the new technology to a higher optimistic readiness level. As result, the assessed technology reduces significantly its environmental impacts, placing in similar scale as the conventional technology. Further investigation showed that a weight reduction from design and topology optimization, and incorporation of the use phase in the analysis is crucial to obtain competitive results from the innovative technology. The ex-ante assessment developed in this work can be applied in different assessments of new and emerging technologies, solving uncertainty constrains, and supporting the improvement of the process from an eco-design point of view.

Future challenges proposed are related with an automated and deeper analysis of emerging technologies, being able to build up calculation model that can evaluate multiple parameters with several values and uncertainty rates at the same time, likely through the use of computer software. Also, a standardized approach in the field will be valuable, to enable more accurate comparison and integration of diverse research.

Although each publication from the different studies that conform this thesis contains its own conclusions, as already mentioned, some general and related conclusions can be drawn based on the knowledge arise from its development and iterative process.

The objective of this thesis was to develop a framework for the environmental evaluation of new metallics materials in the industrial field, identifying important hotspots, and contributing ultimately with a predictive modelling to optimize the design of manufacturing process for application in advanced composite materials. Thus, this thesis proves that Life Cycle Assessment, and its derived methodologies and prospective models generated within it, are a powerful tool to achieve relevant findings and contribute to the advancement in materials science and engineering from a sustainable perspective.

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