Ecological Indicators 144 (2022) 109442

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Original Articles

Comparative Life Cycle Assessment of Green Sand Casting and Low Pressure Die Casting for the production of self-cleaning AlMg3-TiO_2 Metal Matrix Composite

Mario Santiago-Herrera [a], Jesús Ibáñez [a], Julieta Díez-Hernández [b], Juan Antonio Tamayo-Ramos [a], Thomas Pabel [d], Christian Kneissl [d], J.M. Alegre [c], Sonia Martel-Martín [a,*], Rocío Barros [a,*]

[a] International Research Center in Critical Raw Materials for Advanced Industrial Technologies (ICCRAM), University of Burgos, Centro de I+D+I. Plaza Misael Bañuelos s/n, 09001 Burgos, Spain
[b] Department of Economics and Business Administration, Faculty of Economic and Business Sciences, University of Burgos, Calle Parralillos, s/n, 09001 Burgos, Spain
[c] Structural Integrity Research Group, Universidad de Burgos, Avenida Cantabria s/n, 09006 Burgos, Spain
[d] Austrian Foundry Research Institute, 8700 Leoben, Austria

ARTICLE INFO

Keywords:
Metal matrix composites
Life cycle assessment
Low pressure die casting
Green sand casting
Titanium oxide
Aluminium alloy

ABSTRACT

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 paper 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 TiO_2 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 CO_2 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.

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

Abbreviations: LCA, Life Cycle Assessment; GSC, Green Sand Casting; LPDC, Low Pressure Die Casting; MMCs, Metal Matrix Composites; NMVOC, Non-Methane Volatile Organic Compounds; PM2.5, particulate matter; CTUh, Comparative Toxic Unit for human; CTUe, Comparative Toxic Unit for ecotoxicity impacts; NPs, Nanoparticles.

* Corresponding authors.
E-mail addresses: smartel@ubu.es (S. Martel-Martín), rbarros@ubu.es (R. Barros).

https://doi.org/10.1016/j.ecolind.2022.109442
Received 15 March 2022; Received in revised form 26 July 2022; Accepted 9 September 2022
Available online 18 September 2022

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 TiO_2, known too as titanium oxide or titania, the naturally occurring oxide of titanium, as the reinforcing ceramic. TiO_2 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 TiO_2 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 TiO_2-based materials to eliminate bacteria under UV or visible irradiation, and remove contaminants by favouring the spread of water (Liu et al., 2014). TiO_2 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 TiO_2 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 TiO_2 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 CO_2 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-González 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.

2. Case study

Two different manufacturing lines (GSC and LPDC) owned by ÖGI (Österreichisches Gieβerei-Institut - Austrian Foundry Research Institute), in pilot phase for the use of the novel MMC (AlMg3-TiO_2), were studied to analyse their resources consumption, energy expenditure, waste production and final products. Fig. 1 and Fig. 2 display the GSC and LPDC, respectively.

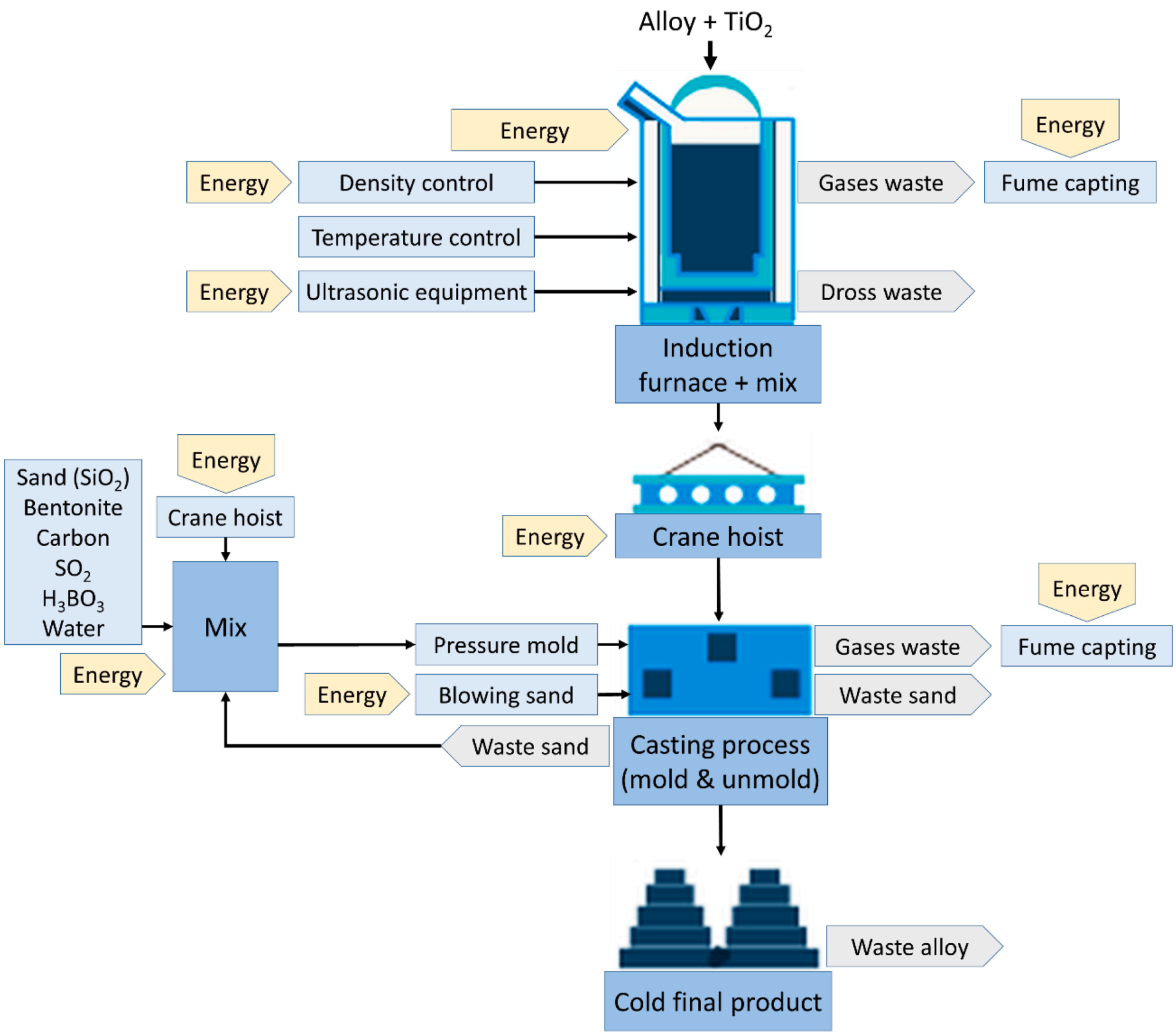

Fig. 1. The Green Sand Casting Process, defined by ÖGI, entails the following processes: 1. Materials are introduced in an induction furnace; 2. Density and temperature control tests are carried out; 3. Gases are captured by a fume extractor to avoid high environmental impacts; 4. The material mix is 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. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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

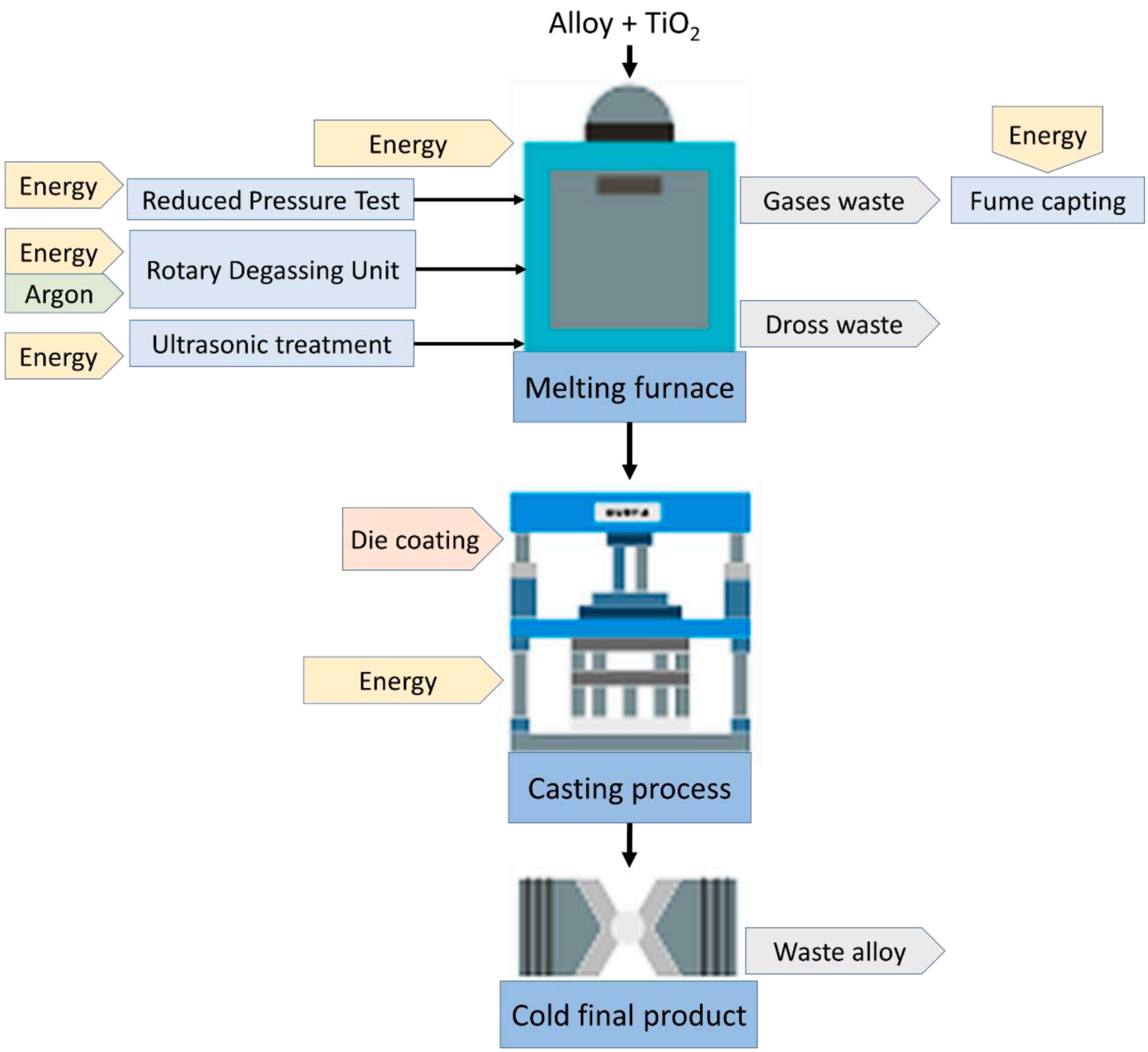

Fig. 2. The Low Pressure Die Casting Process, defined by ÖGI, entails the following processes: 1. Introduction of the alloy into the melting furnaces; 2. Degassing process using argon and a rotary unit; 3. Ultrasonic treatment; 4. Reduced pressure test is carried out; 5. Casting process; 6. Obtain of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

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.

3.1. 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 TiO_2 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.

3.2. 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.

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. 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 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	30,000	6	180	heated for 6 h. ingots melting 30 min
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	15,000	1	15	in use 60 min
Compressed air blowing system	15,000	0,1	1,5	6 min 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 -greater than 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	50,000	6	300	heating 6 h
Rotary degassing unit	560	0,75	0,42	in use 30 min to 1 h
Ultrasonic equipment	4500	0,16	0,72	in use 10 min
Casting process LPDC	11,000	6	66	casting 6 h
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		6 L/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	

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. 3 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

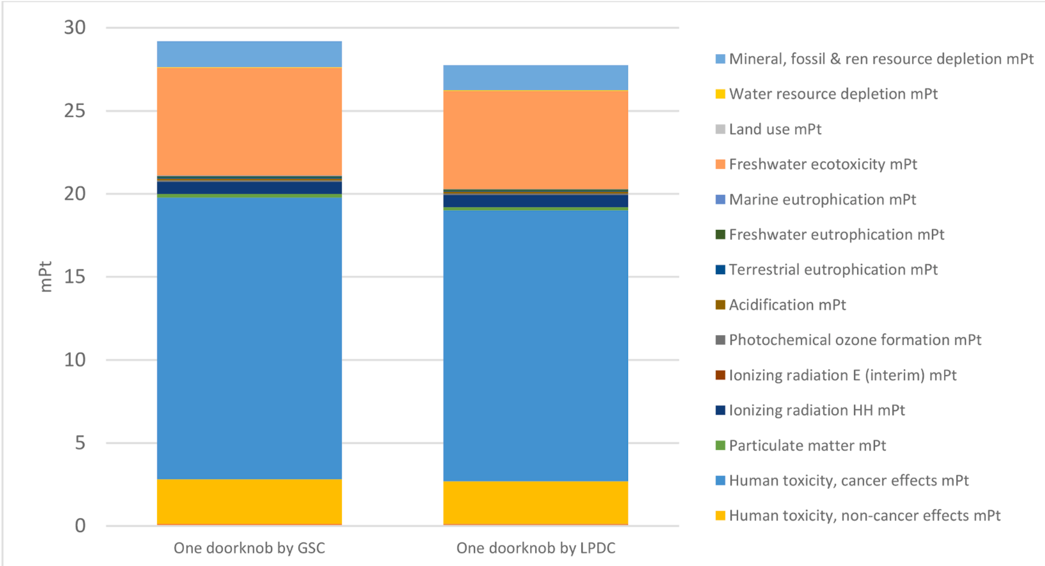

Fig. 3. Weighting (single score) comparative between GSC and LPDC.

comparison matrix chart that facilitates the interpretation of results (Fig. 4).

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. 5 displays a comparison with the respective initial scenarios. The weighting score for this assessment can be found in the Supplementary Material, Table S8.

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 CO_2 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

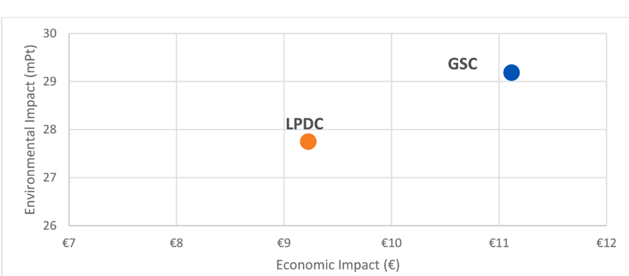

Fig. 4. Comparison matrix chart of both technologies, GSC and LPDC, with the environmental impact measured in mPt and the economic impact measured in €.

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

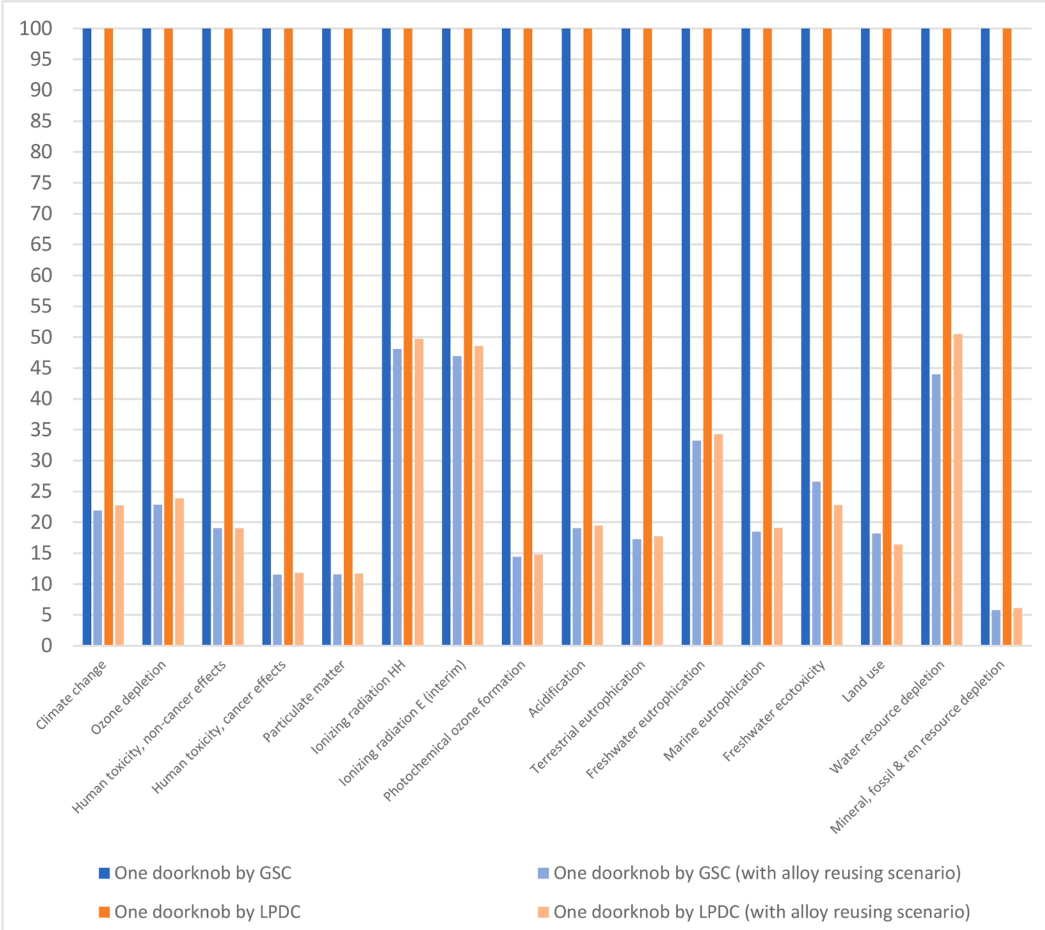

Fig. 5. Impact category comparative characterization results between GSC and LPDC with their respective potential reusing scenario.

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 TiO_2, 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 CO_2 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.

4. Conclusion

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.

CRediT authorship contribution statement

Mario Santiago-Herrera: Conceptualization, Investigation, Methodology, Data curation, Software, Writing – original draft, Writing – review & editing. **Jesús Ibáñez Porras:** . **Julieta Díez Hernández:** . **Juan Antonio Tamayo-Ramos:** Funding acquisition, Supervision, Writing – review & editing. **Thomas Pabel:** . **Christian Kneissl:** . **J.M. Alegre:** Writing – review & editing, Supervision. **Sonia Martel Martín:** Funding acquisition, Conceptualization, Supervision. **Rocío Barros:** Funding acquisition, Conceptualization, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This research has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant Agreement No. 826312) in the context of the LightMe project. It has also received funds from Board of Education of Junta de Castilla y León and the European Social Fund (EDU/1508/2020). The authors want to acknowledge the support of ÖGI (Österreichisches Gießerei-Institut) for the data about processes.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2022.109442.

References

Baskaran, G., Lawrence, I.D., Kannan, C.R., Stalin, B., 2015. Characterization of aluminium based metal matrix composite reinforced with TiC and TiO2. Int. J. Appl. Eng. 10 (51), 682–687.

Lorenzo, Benini, Lucia, Mancini, Serenella, Sala, Simone, Manfredi, Erwin, Schau, Rana, Pant, 2014. Normalisation method and data for Environmental Footprints. Publications Office of the European Union. https://doi.org/10.2788/16415.

Bulei, C., Kiss, I., Alexa, V., 2020. Development of metal matrix composites using recycled secondary raw materials from aluminium wastes. Mater. Today:. Proc. 45, 4143–4149. https://doi.org/10.1016/j.matpr.2020.11.926.

European Commission. (2014). *Environmental Footprint Pilot Guidance document. Guidance for the implementation of the EU Product Environmental Footprint (PEF) during the Environmental Footprint (EF) pilot phase, v. 4.0*.

Dalquist, S., Gutowski, T., 2004. Life cycle analysis of conventional manufacturing techniques: die casting. American Society of Mechanical Engineers, Manufacturing Engineering Division, MED 15 (December), 631–641. https://doi.org/10.1115/IMECE2004-62599.

European Commission - Joint Research Centre - Institute for Environment and Sustainability. (2012). Characterisation factors of the ILCD Recommended Life Cycle Impact Assessment methods. In *European Commission*.

European Commission, J.R.C., 2010. International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance. Insititute of Environment and Sustainability. https://doi.org/10.2788/94987.

Ferreira, V., Egizabal, P., Popov, V., García de Cortázar, M., Irazustabarrena, A., López-Sabirón, A.M., Ferreira, G., 2019. Lightweight automotive components based on nanodiamond-reinforced aluminium alloy: A technical and environmental evaluation. Diam. Relat. Mater. 92, 174–186. https://doi.org/10.1016/j.diamond.2018.12.015.

Frischknecht, R., Braunschweig, A., Hofstetter, P., Suter, P., 2000. Human health damages due to ionising radiation in life cycle impact assessment. Environ. Impact Assess. Rev. 20 (2), 159–189. https://doi.org/10.1016/S0195-9255(99)00042-6.

Frischknecht, R., Steiner, R., Arthur, B., Norbert, E., Gabi, H., 2006. Swiss Ecological Scarcity Method: The New Version 2006. Proceedings of the 7th International Conference on EcoBalance.

Fu, P., Luo, A.A., Jiang, H., Peng, L., Yu, Y., Zhai, C., Sachdev, A.K., 2008. Low-pressure die casting of magnesium alloy AM50: Response to process parameters. J. Mater. Process. Technol. 205 (1-3), 224–234.

Fujishima, A., Zhang, X., Tryk, D.A., 2008. TiO2 photocatalysis and related surface phenomena. Surf. Sci. Rep. 63 (12), 515–582. https://doi.org/10.1016/J.SURFREP.2008.10.001.

Garnier-Laplace, J., Beaugelin-Seiller, K., Gilbin, R., Della-Vedova, C., Jolliet, O., Payet, J., 2009. A Screening Level Ecological Risk Assessment and ranking method for liquid radioactive and chemical mixtures released by nuclear facilities under normal operating conditions. Radioprotection 44 (5), 903–908. https://doi.org/10.1051/RADIOPRO/20095161.

Goedkoop, M., Heijungs, R., de Schryver, A., Struijs, J., van Zelm, R., 2009. ReCiPe 2008 A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Characterisation Factors, first edition, Report I.

Greco, S.L., Wilson, A.M., Spengler, J.D., Levy, J.I., 2007. Spatial patterns of mobile source particulate matter emissions-to-exposure relationships across the United States. Atmos. Environ. 41 (5), 1011–1025. https://doi.org/10.1016/J.ATMOSENV.2006.09.025.

Guinée, J.B. (Ed.), Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Wegener Sleeswijk, A., Suh, S.,. Udo de Haes, H.A, De Bruijn, J.A., & van Duin, R., Huijbregts, M.A.J. (2002). *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards.* Kluwer Academic Publishers. https://doi.org/10.1007/0-306-48055-7.

Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I., 2017. Life Cycle Assessment: Theory and Practice. In: Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I. (Eds.), Life Cycle Assessment: Theory and Practice. Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3.

Huang, Z., Maness, P.C., Blake, D.M., Wolfrum, E.J., Smolinski, S.L., Jacoby, W.A., 2000. Bactericidal mode of titanium dioxide photocatalysis. J. Photochem. Photobiol., A 130 (2–3), 163–170. https://doi.org/10.1016/S1010-6030(99)00205-1.

IPCC. (2007). *IPCC Climate Change Fourth Assessment Report*. https://www.ipcc.ch/assessment-report/ar4/.

Irhayyim, S.S., Hammood, H.S., Abdulhadi, H.A., 2019. Effect of nano-TiO2 particles on mechanical performance of Al-CNT matrix composite. AIMS Materials Science 6 (6), 1124–1134. https://doi.org/10.3934/matersci.2019.6.1124.

ISO. (2006b). Environmental Management. Life Cycle Assessment - Requirements and Guidelines. (ISO 14044:2006). In *International Organization for Standardization* (Vol. 3, Issue 571). http://tienda.icontec.org/brief/NTC-ISO14044.pdf.

ISO, 2006. 14040: Environmental management–life cycle assessment—Principles and framework. International Organization for Standardization.

Iwatsu, M., Kanetaka, H., Mokudai, T., Ogawa, T., Kawashita, M., Sasaki, K., 2020. Visible light-induced photocatalytic and antibacterial activity of N-doped TiO2. Journal of Biomedical Materials Research - Part B Applied Biomaterials 108 (2), 451–459. https://doi.org/10.1002/jbm.b.34401.

Khan, M.M., Singh, M., Jadhav, G.N., Mahajani, S.M., Mandre, S., 2020. Characterization of Waste and Reclaimed Green Sand Used in Foundry Processing. Silicon 12 (3), 677–691. https://doi.org/10.1007/s12633-019-00146-0.

Lata, S., Pandey, A., Labhansh, S., Meena, A.K., Rana, R., Lal, R., 2018. An Experimental Study and Analysis of the Mechanical Properties of Titanium Dioxide Reinforced Aluminum (AA 5051) Composite. Mater. Today:. Proc. 5 (2), 6090–6097. https://doi.org/10.1016/J.MATPR.2017.12.214.

Liu, K., Cao, M., Fujishima, A., Jiang, L., 2014. Bio-Inspired Titanium Dioxide Materials with Special Wettability and Their Applications. Chem. Rev. 114 (19), 10044–10094. https://doi.org/10.1021/CR4006796.

Merchán, M., Egizabal, P., García de Cortázar, M., Irazustabarrena, A., Galarraga, H., 2019. Development of an Innovative Low Pressure Die Casting Process for Aluminum Powertrain and Structural Components. Adv. Eng. Mater. 21 (6), 1800105.

Milà i Canals, L., Romanyà, J., Cowell, S.J., 2007. Method for assessing impacts on life support functions (LSF) related to the use of 'fertile land' in Life Cycle Assessment (LCA). J. Cleaner Prod. 15 (15), 1426–1440.

Naik, S., Das, S.R., Dhupal, D., 2021. Experimental Investigation, Predictive Modeling, Parametric Optimization and Cost Analysis in Electrical Discharge Machining of Al-SiC Metal Matrix Composite. Silicon 13 (4), 1017–1040. https://doi.org/10.1007/s12633-020-00482-6.

Nargundkar, A., Shastri, A., 2020. Optimization of sand usage for metal casting process-a sustainable manufacturing approach. Int. J. Sci. Res. 9, 2.

Ou, J., Wei, C., Cockcroft, S., Maijer, D., Zhu, L., A, L., Li, C., Zhu, Z., 2020. Advanced Process Simulation of Low Pressure Die Cast A356 Aluminum Automotive Wheels—Part I, Process Characterization. *Metals* 10 (5), 563.

Padmanabhan, N.T., John, H., 2020. Titanium dioxide based self-cleaning smart surfaces: A short review. J. Environ. Chem. Eng. 8 (5), 104211 https://doi.org/10.1016/j.jece.2020.104211.

Pagone, E., Salonitis, K., Jolly, M., 2018. Energy and material efficiency metrics in foundries. Procedia Manuf. 21, 421–428. https://doi.org/10.1016/j.promfg.2018.02.140.

Posch, M., Seppälä, J., Hettelingh, J.P., Johansson, M., Margni, M., Jolliet, O., 2008. The role of atmospheric dispersion models and ecosystem sensitivity in the determination of characterisation factors for acidifying and eutrophying emissions in LCIA. Int. J. Life Cycle Assess. 13 (6), 477–486. https://doi.org/10.1007/S11367-008-0025-9.

Rabl, A., & Spadaro, J.V. (2004). *The RiskPoll software, version is 1.051 (datedAugust 2004)*. http://arirabl.org/software/.

Ranade, P.B., Reddy, G., Koppal, P., Paithankar, A., Shevale, S., 2020. Implementation of DMAIC methodology in green sand-casting process. Mater. Today:. Proc. 42, 500–507. https://doi.org/10.1016/j.matpr.2020.10.475.

Rodríguez-González, P., Fernández-Abia, A.I., Castro-Sastre, M.A., Robles, P.E., Barreiro, J., Leo, P., 2019. Comparative Study of Aluminum Alloy Casting obtained by Sand Casting Method and Additive Manufacturing Technology. Procedia Manuf. 41, 682–689. https://doi.org/10.1016/j.promfg.2019.09.058.

Rosenbaum, R.K., Bachmann, T.M., Gold, L.S., Huijbregts, M.A.J., Jolliet, O., Juraske, R., Koehler, A., Larsen, H.F., MacLeod, M., Margni, M., McKone, T.E., Payet, J., Schuhmacher, M., van de Meent, D., Hauschild, M.Z., 2008. USEtox - The UNEP-SETAC toxicity model: Recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. Int. J. Life Cycle Assess. 13 (7), 532–546. https://doi.org/10.1007/S11367-008-0038-4/TABLES/2.

Salonitis, K., Jolly, M., Zeng, B., 2017. Simulation Based Energy and Resource Efficient Casting Process Chain Selection: A Case Study. Procedia Manuf. 8, 67–74. https://doi.org/10.1016/j.promfg.2017.02.008.

Salonitis, K., Jolly, M., Pagone, E., Papanikolaou, M., 2019. Life-cycle and energy assessment of automotive component manufacturing: The dilemma between aluminum and cast iron. Energies 12 (13), 2557. https://doi.org/10.3390/en12132557.

Seppälä, J., Posch, M., Johansson, M., Hettelingh, J.-P., 2006. Country-dependent Characterisation Factors for Acidification and Terrestrial Eutrophication Based on Accumulated Exceedance as an Impact Category Indicator (14 pp). Int J Life Cycle Assessment 11 (6), 403–416.

Spanou, S., Kontos, A.I., Siokou, A., Kontos, A.G., Vaenas, N., Falaras, P., Pavlatou, E.A., 2013. Self cleaning behaviour of Ni/nano-TiO2 metal matrix composites. Electrochim. Acta 105, 324–332. https://doi.org/10.1016/j.electacta.2013.04.174.

Srinivasan, A., Pillai, U.T.S., John, V., Pai, B.C., 2005. LOW-PRESSURE CASTING OF LM25 (Al-7Si-0.3 Mg) ALUMINIUM ALLOY. Mater. Manuf. Processes 20 (2). https://doi.org/10.1081/AMP-200041867.

Sun, J., Le, Q., Fu, L., Bai, J., Tretter, J., Herbold, K., Huo, H., 2019. Gas entrainment behavior of aluminum alloy engine crankcases during the low-pressure-die-casting process. J. Mater. Process. Technol. 266, 274–282. https://doi.org/10.1016/j.jmatprotec.2018.11.016.

van Zelm, R., Huijbregts, M.A.J., den Hollander, H.A., van Jaarsveld, H.A., Sauter, F.J., Struijs, J., van Wijnen, H.J., van de Meent, D., 2008. European characterization factors for human health damage of PM10 and ozone in life cycle impact assessment. Atmos. Environ. 42 (3), 441–453. https://doi.org/10.1016/J.ATMOSENV.2007.09.072.

Vijaya Ramnath, B., Parswajinan, C., Dharmaseelan, R., Thileepan, K., Nithin Krishna, K., 2021. A review on aluminium metal matrix composites. Mater. Today:. Proc. https://doi.org/10.1016/j.matpr.2021.03.600.

Wachesk, C.C., Seabra, S.H., Dos Santos, T.A.T., Trava-Airoldi, V.J., Lobo, A.O., Marciano, F.R., 2021. In vivo biocompatibility of diamond-like carbon films containing TiO2 nanoparticles for biomedical applications. J. Mater. Sci. - Mater. Med. 32 (9), 1–10. https://doi.org/10.1007/S10856-021-06596-6/FIGURES/6.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21 (9), 1218–1230. https://doi.org/10.1007/s11367-016-1087-8.

WMO, W. M. O. (1999). *Scientific Assessment of Ozone Depletion: 1998. Global Ozone Research and Monitoring Project - Report No. 44.* WMO.

Yadav, A., Jamwal, A., Agrawal, R., Kumar, A., 2021. Environmental impacts assessment during sand casting of Aluminium LM04 product: A case of Indian manufacturing industry. Procedia CIRP 98, 181–186. https://doi.org/10.1016/j.procir.2021.01.027.

Zheng, J., Chen, A., Zheng, W., Zhou, X., Bai, B., Wu, J., Ling, W., Ma, H., Wang, W., 2020a. Effectiveness analysis of resources consumption, environmental impact and production efficiency in traditional manufacturing using new technologies: Case from sand casting. Energy Convers. Manage. 209, 112671.

Zheng, J., Zhou, X., Yu, Y., Wu, J., Ling, W., Ma, H., 2020b. Low carbon, high efficiency and sustainable production of traditional manufacturing methods through process design strategy: Improvement process for sand casting defects. J. Cleaner Prod. 253, 119917 https://doi.org/10.1016/j.jclepro.2019.119917.