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Environmental performance analysis of hybrid manufacturing of closed impellers

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Environmental performance analysis of hybrid manufacturing of closed impellers

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Abstract

The environmental impact of the hybrid manufacturing of a closed impeller was compared to the one generated using conventional investment casting. Laser directed energy deposition and milling were used to manufacture the component while the data for the investment casting was retrieved from literature. Life cycle assessments were performed on both processes. The results showed that the hybrid manufacturing of the impeller had a higher environmental impact under the Climate Change impact category. The environmental impact of hybrid manufacturing was analyzed within each of its stages and hotspots were identified. Recommendations for improvement for further studies in the field are provided.

Keywords: hybrid manufacturing; laser directed energy deposition; sustainability; environmental performance; life cycle assessment; carbon footprint

1. Introduction

Impellers are turbomachinery components designed to rotate at high speeds to increase a fluid's pressure and flow rate. Three types of impellers can be identified: open, semi-closed, and closed [1]. The difference lies in their designs that include a back and front wall around the vanes for the closed impeller, as compared to the semi-closed one that only has a back wall, and the open impeller that does not include any walls. The goal of adding walls is mainly to increase the component strength. Closed impellers are primarily found in larger pumps and applied to suspended-solid systems [2].

There are three traditional methods of manufacturing closed impellers, the oldest being the three-piece construction method [3]. The hub, blades, and cover are manufactured separately through hot working and machining. Pieces are then joined together through riveting and welding. In order to improve the process gaps, it developed into a two-piece, then a one-piece construction method, the investment casting [4]. The aim was to reduce the intensity of manual labor and number of joints between pieces which could lead to defects. In fact, as reported by Laney et al. [4], 'welds are a necessary evil that should be considered defects between two perfectly good pieces of metal'. Thus, justifying the progression to the one-piece construction method. This process unfortunately, brought on its own set of challenges such as the tool limitations, in terms of accessibility, reach, and size, during the finishing phases. Additionally, it was found that there is a higher percentage of forged/cast material wasted [5].

As technology advances, there is an increased popularity of terms such as 'sustainability', the need to enforce sustainable manufacturing, and the importance of reducing the wastes and greenhouse gas (GHG) emissions that could prove harmful to the environment. Therefore, instead of a purely subtractive manufacturing that is more likely related to the production of waste, additive manufacturing technologies such as laser directed energy deposition (L-DED) and laser powder bed fusion (L-PBF) are considered as an effort to reduce raw materials depletion, leftover production, and help move towards a sustainable manufacturing [2].

According to the 2017 Sulzer Industrial Report [6], it is possible to produce an impeller through L-DED in a shorter time as compared to traditional methods. Additionally, combining the use of additive manufacturing with a computer aided design / manufacturing (CAD/CAM) software tool and a 5-axis milling machine would produce a hybrid manufacturing concept that could potentially heighten repair capabilities. This entails the possibility of producing or

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repairing complex parts, minimizing production time, reducing material wastage, process cost reduction, and even reducing the environmental impact of the overhaul process.
This paper aims to quantify the environmental impact generated by the implementation of hybrid manufacturing against conventional investment casting of closed impellers.

2. Methodology

A CAD drawing of the closed impeller considered in this study is reported in Figure 1.

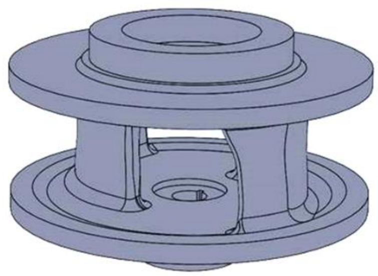

Figure 1: Closed impeller design used for hybrid manufacturing

For its hybrid manufacturing a DMG MORI Lasertec 65 DED Hybrid machine (https://en.dmgmori.com/products/machines/additive-manufacturing/powder-nozzle/lasertec-65-ded-hybrid) was employed, a five-axis computer numerical control (CNC) system with additive (L-DED) and subtractive (milling) capabilities. This equipment is provided with a 2.5 kW max. power diode laser (λ = 1.020 µm) with top-hat profile and fixed spot sizes of 1.6 mm and 3.0 mm. Commercially available stainless steel 316L (SS316L) powder with particles in the range 45-105 µm was used. The powder was provided by Carpenter Additive (https://www.carpenteradditive.com/) and produced via gas atomization process. Argon gas was used as both carrier and shielding gas during the process. A SS316L disc of ø 200 mm and thickness 40 mm was used as substrate and machined into the impeller bottom plate. For the generation of the toolpaths used in the manufacturing process, both additive and subtractive, the CAD/CAM software Siemens NX 12 was used (https://www.plm.automation.siemens.com/global/en/products/nx/).
The environmental performance analysis reported in this paper aims to compare the impacts associated to the manufacturing of one closed impeller via L-DED + machining hybrid technology and compare them to those linked to the use of investment casting. A life cycle assessment (LCA) was conducted for this purpose. While the data for the hybrid process were generated through direct technical work at the Advanced Remanufacturing and Technology Centre (ARTC) of Singapore, those for the casting were extracted from literature, in particular from Anderson et al. [7]. To be noted that one of the main advantages of the investment casting process is to require a minimal machining (grinding) due to the smoother surface quality obtained with respect to sand casting [8]. The information needed for the LCA modelling of the initial stage, called Pre-Manufacturing, where the feedstock powder is produced for the L-DED process, was also retrieved from Anderson et al. [7]. For reference, a schematic representation of the main steps of the investment casting process is reported in Figure 2 [9].

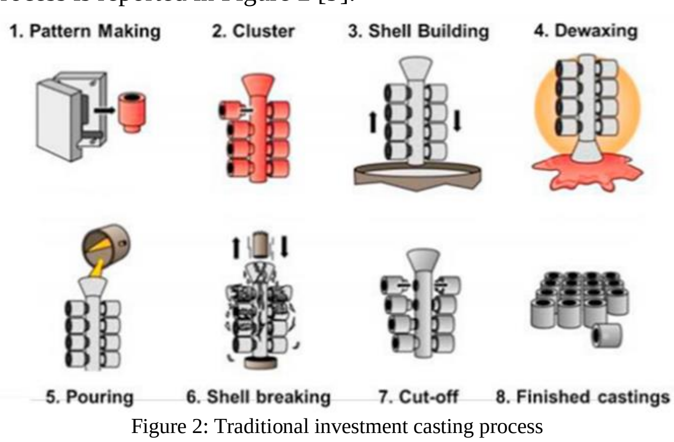

Figure 2: Traditional investment casting process

The LCA procedure is governed by the following standards: ISO 14040:2006 (Environmental management. Life Cycle Assessment. Principles and framework), ISO 14044:2006 (Environmental management. Life Cycle Assessment. Requirements and guidelines) and ISO/TR 14047:2012 (Illustrative examples on how to apply ISO 14044 to impact assessment situations). The LCA process can be divided into four steps: goal definition and boundary conditions, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation of the LCIA results. The overall methodology followed for the LCA reported in this paper is represented in Figure 3.

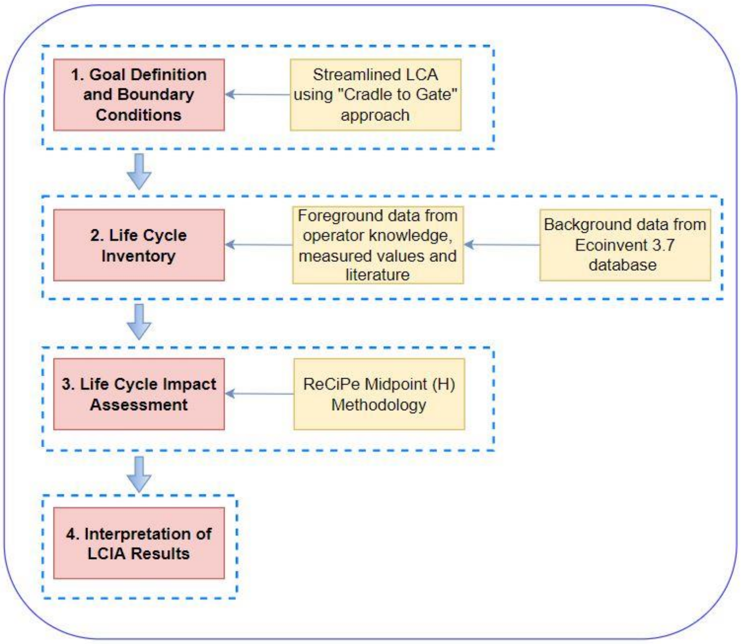

Figure 3: LCA methodology followed in this study

The functional unit (FU) enables the environmental impacts of multiple comparative studies to be measured to a single point of reference. The environmental impact arising from the manufacturing of one closed impeller of mass 11.56 kg was selected as FU for the LCA and a streamlined cradle-to-gate boundary condition was used. This includes the stages of raw materials production (pre-manufacturing) and the manufacturing process itself, either through hybrid manufacturing or investment casting. The stages of manufactured product transportation, usage, and disposal were not included in this study. Detailed information on the system boundaries is represented in Figure 4 with individual processes shown in pink, inputs in yellow, and outputs in green boxes.

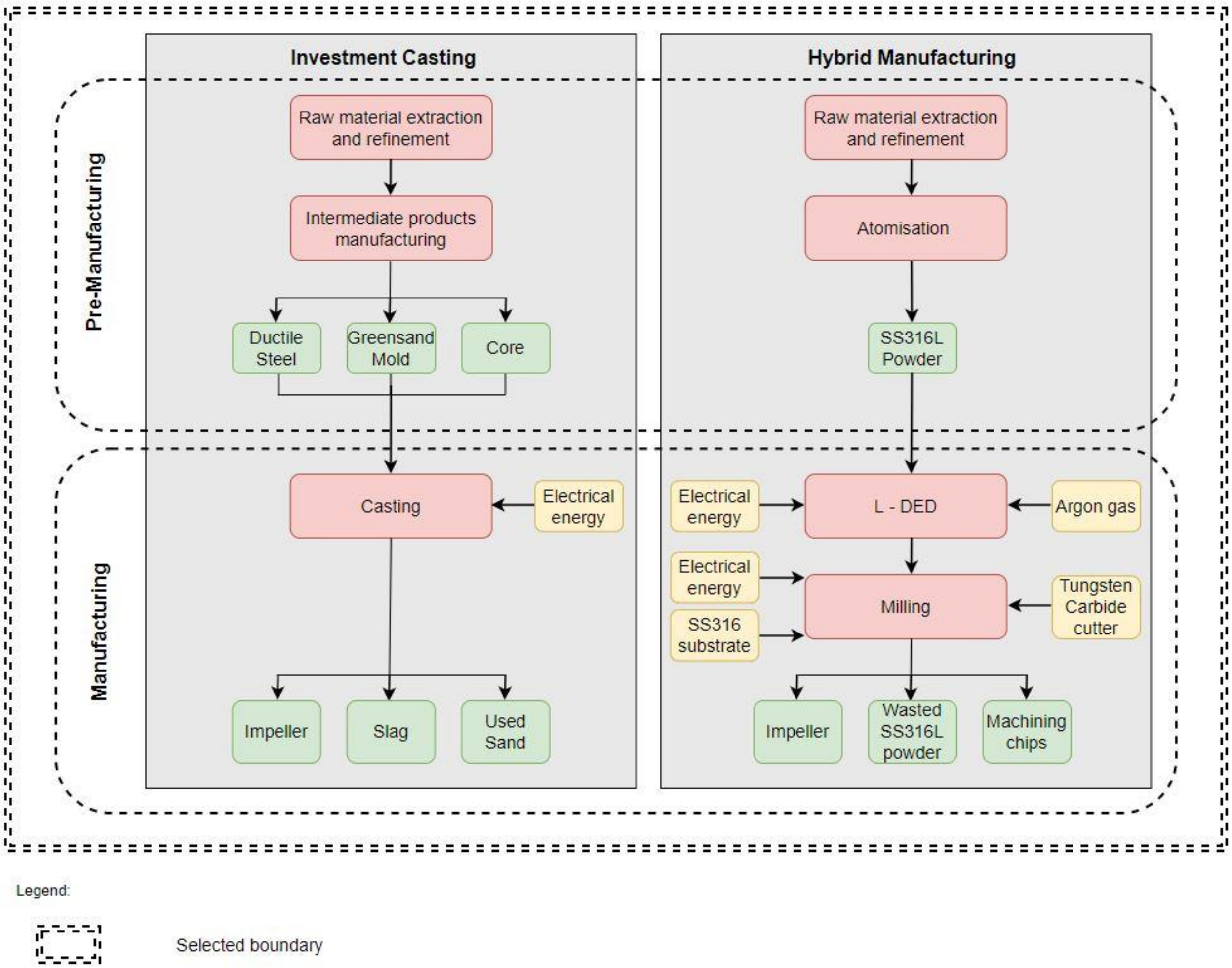

Figure 4: System boundaries considered in this study

The GaBi software (https://gabi.sphera.com/international/index/) was used for the modelling and the background information was taken from the ecoinvent 3.7 database (https://ecoinvent.org/the-ecoinvent-database/data-releases/ecoinvent-3-7-1/). The geographical locations of the processes in both manufacturing techniques are not specified in the modelling and the background values taken from ecoinvent database were global averages to simplify the analysis. Where global average values for the processes were not found in the database, European average values were used. In the modelling, only the L-DED and the milling processes of hybrid manufacturing used Singapore specific background data, namely the electricity grid mix of Singapore, where the actual manufacturing took place. The environmental impact of the wasted materials from both manufacturing techniques were also modelled using global or European average processes from the ecoinvent database.

In the LCIA step, the environmental impacts generated by the two different processes were analyzed. The ReCiPe Midpoint (H) methodology was employed (https://gabi.sphera.com/support/gabi/gabi-lcia-documentation/recipe/), and the Climate Change midpoint impact category was selected for analysis. The midpoint characterization factor used was the popular Global Warming Potential 100 years (GWP-100 years). The ReCiPe method is a combination of the CML methodology (which calculates midpoint indicators) and the ecoindicator methodology (which calculates endpoint indicators). The hierarchist (H) cultural perspective is based on the medium timeframe of 100 years for GWP [10]. The Climate Change assessment of both manufacturing techniques have been visualized and explained in the subsequent section of the study. The classification and characterization of the LCI results were performed using the GaBi software.

Finally, in the last step of the LCA, the results of the LCI and LCIA are studied, according to the ISO standards 14040:2006, 14044:2006, and 14047:2012. The results must be adequately analyzed, transparently reported and in line with the goals of the study [11].

3. Results & Discussion

The complete procedure and process parameters used to manufacture the closed impeller by hybrid manufacturing cannot be disclosed due to a confidentiality agreement with the ARTC's industrial member voestalpine Additive Manufacturing Center Singapore Pte. Ltd. (vAMCS), main sponsor for this project. A summarized schematic representation of the step-by-step procedure followed is reported in Figure 5. For each reported step, an image from the CAD/CAM software and a picture taken during the manufacturing phases are reported. As can be seen, the SS316L disc was used as base plate and the blades were initially deposited and machined. The next step was the manufacturing of the top plate, followed by a last step of final machining. A total of 9.78 kg of SS316L powder was used to manufacture the impeller, in addition to the SS316L baseplate (10.30 kg). The final product had a mass of 11.56 kg. A total cycle time of approximatively 60 hours was measured, where 21 hours were dedicated to L-DED and 39 hours to machining.

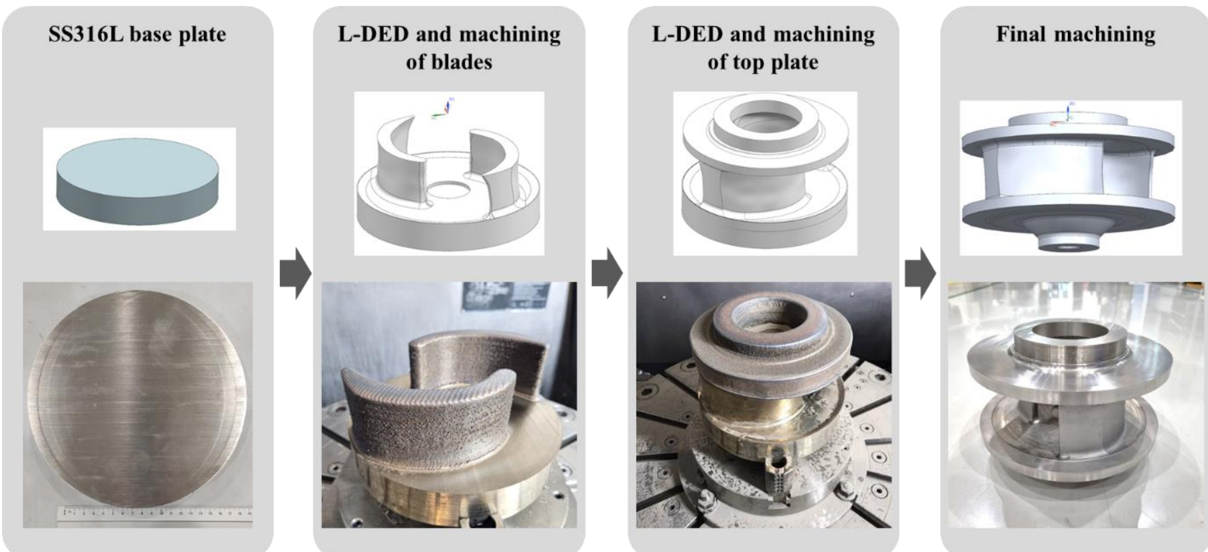

Figure 5: Hybrid manufacturing of closed impeller

In the LCI step, the materials used, the energy consumed, and the emission released were quantified and modelled based on the considered FU. The inputs in the hybrid manufacturing process were the L-DED raw materials (SS316L powder and substrate), Argon gas, machining inserts/cutters (tungsten carbide), and electricity. To be noted that the coolant needed during the milling phase was not accounted in the model as the machine uses a closed-loop circuit and the losses can be considered negligible for the duration of the impeller manufacturing. For investment casting, the inputs were iron sinter, sand, bentonite, coal dust, phenol-formaldehyde resin, water, and electricity. Figure 6 and Figure 7 show in detail the quantity of inputs and outputs used in the modelling of investment casting and hybrid manufacturing processes respectively.

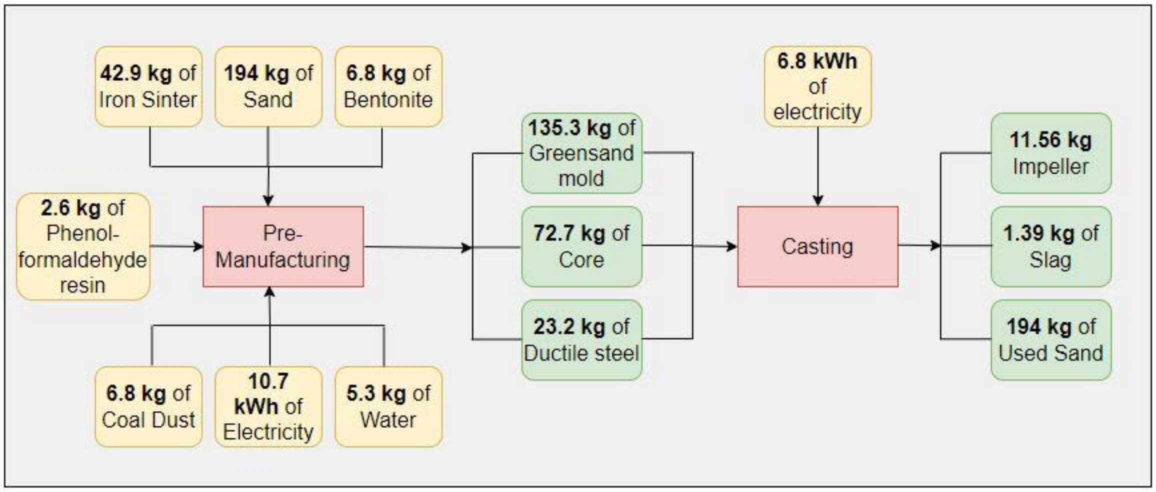

Figure 6: Modelling of pre-manufacturing and manufacturing stages for the FU of one closed impeller (11.56 kg) for investment casting

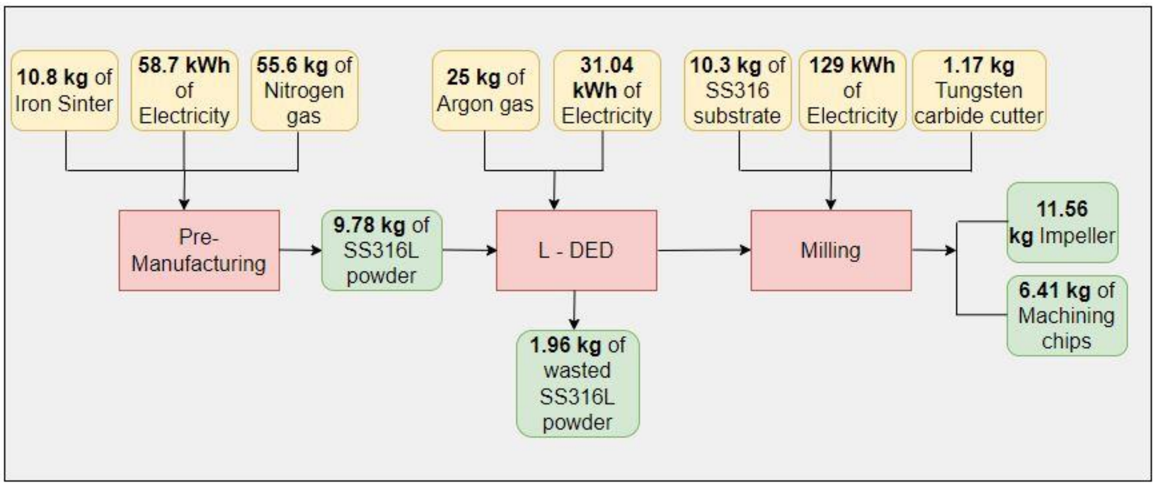

Figure 7: Modelling of pre-manufacturing and manufacturing stages for the FU of one closed impeller (11.56 kg) for hybrid manufacturing

The results of the LCIA conducted using the Gabi software for modelling and ecoinvent 3.7 database are visualized in Figure 8. The total climate change impact, measured in kg of CO_2 equivalent, is 60.69 kg CO_2 eq. for investment casting and 205.36 kg CO_2 eq. for hybrid manufacturing for a 11.56 kg stainless steel impeller. This shows that the environmental impact for this category is more than three times higher for hybrid manufacturing.

In the same figure, the breakdown of the total carbon footprint of each of the manufacturing techniques into its component stages, namely, pre-manufacturing, casting/L-DED, and machining, is illustrated. The pre-manufacturing stage for investment casting consider the manufacturing of intermediate products such as greensand mold, core, and ductile steel while for hybrid manufacturing included the production of the raw SS316L stainless steel powder. The atomization process required for the manufacturing of the metallic powders is a high energy consumption procedure [7]. This explains the higher expenditure for hybrid manufacturing for this stage. Alternative ways to manufacture the raw materials, or to reduce the consumption of virgin powders, will contribute to decrease the emissions and move toward a more sustainable L-DED process [12].

By comparing the manufacturing stages for the two processes, it is possible to appreciate that the L-DED had a higher carbon footprint in comparison to the investment casting. This is mostly caused by the usage of a large amounts of Argon as carrier and shielding gas during the deposition. Modelling the L-DED process using similar volume of Nitrogen as alternative, as also reported by Anderson et al. [7], was seen to reduce the footprint considerably and give similar values for both manufacturing techniques. The possibility of using gas with a smaller carbon footprint can also be a step toward a more sustainable L-DED process.

Finally, the complete validity of the reported assessment needs to be tested using data extracted from experimental work. Another additional source of higher emissions in the hybrid manufacturing process comes from the milling steps, not necessary in investment casting. As can be seen again from Figure 8, milling accounts for approximatively half of the carbon footprint calculated for the hybrid process. However, the electricity data used for this stage, were calculated using the model proposed by Peng et al. [5], that developed it for the milling of a Titanium alloy. With a proper measurement of the electric consumption of the CNC machine, for example through the installation of electricity meter, a more accurate estimation of the milling process emissions could be provided. This will also support the development of more sustainable practices, like the use of alternative machining toolpaths. In addition, the grinding process that may be needed to finish investment casting parts was not modelled in this case as not reported by Anderson et al. [7]. By including this process, the differences in terms of total climate change impact between investment casting and hybrid manufacturing may be reduced.

It has also to be noted that the transportation stage was not considered in the current scope. By including it and increasing the system boundaries to include the end-of-life stages, some variation to the final results may be observed.

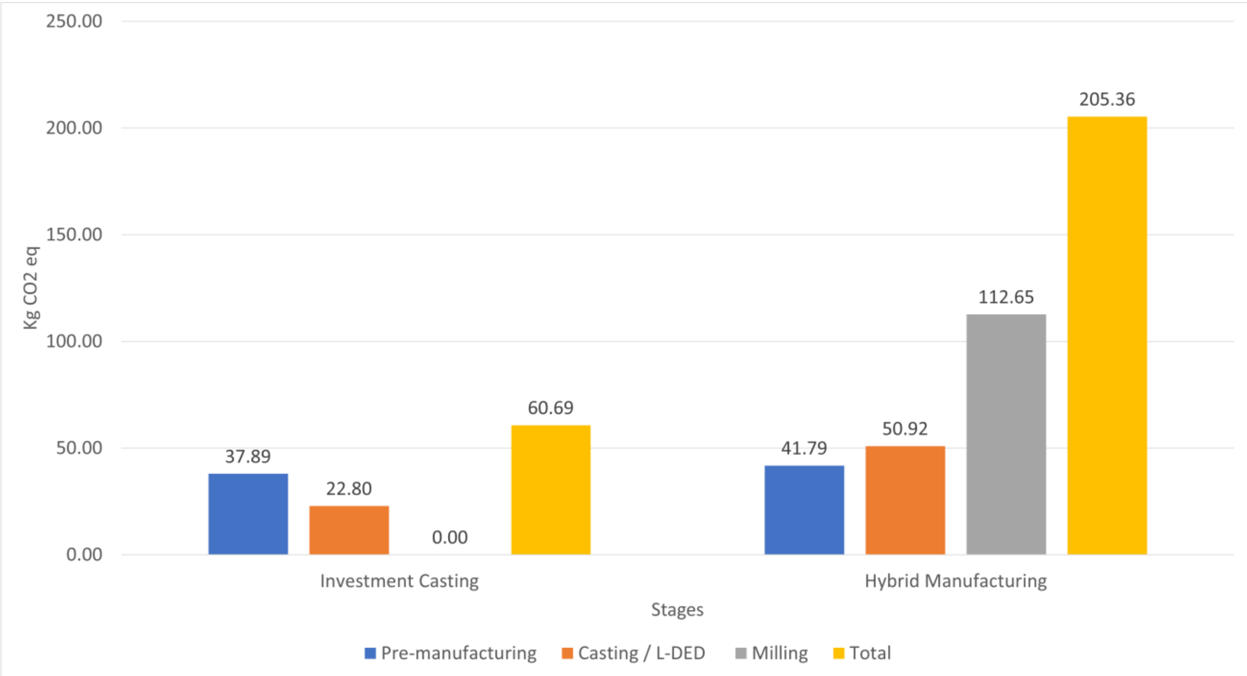

Figure 8: Overall LCIA results – Climate Change impact category (GWP 100 years)

4. Conclusions

The environmental impacts generated by the production of a closed impeller via hybrid manufacturing were compared with those obtained by the production through conventional investment casting. The LCA performed showed that the hybrid manufacturing process had a larger carbon footprint than investment casting, mainly due to the energy intensive atomization process to obtain the raw metallic powder, the use of a significant amount of Argon gas during L-DED, and the significant electricity used by the milling process (estimated value).

The identification of these hotspots permitted to identify areas of improvements to drive the hybrid manufacturing technology toward a more sustainable path: reuse of un-melted powder; use of alternative carrier and shielding gas in L-DED; direct measurements of electrical consumption of CNC centers.

Finally, it has to be highlighted that the modelling of the investment casting was performed starting purely from literature data. The same was done for the pre-manufacturing stage of powder atomization and for the calculation of the energy consumption during milling. Through direct measurements a more accurate modelling can be done, and the reported data may be affected.

Acknowledgements

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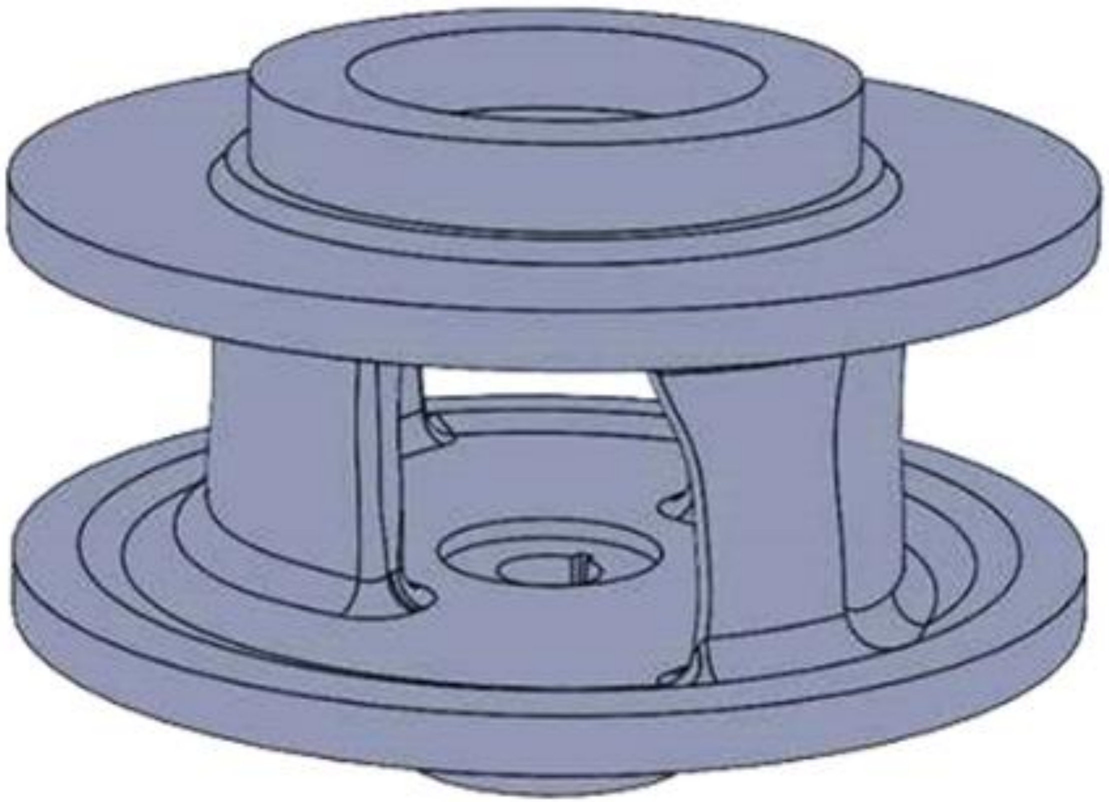
Figure 1

Figure 01



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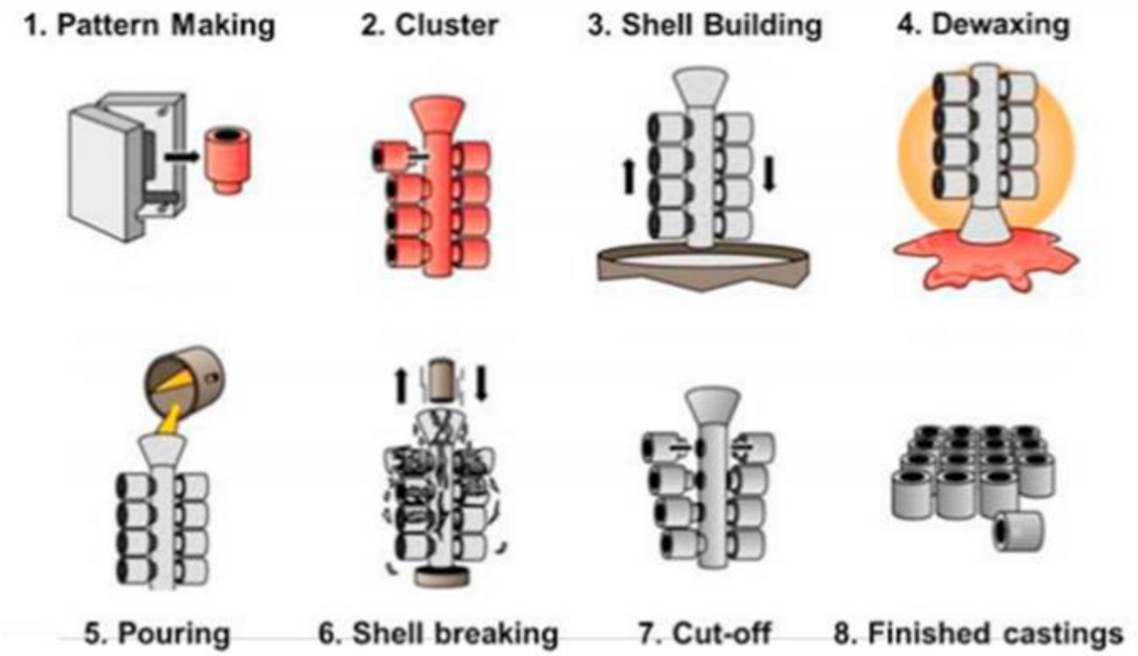

Figure 3
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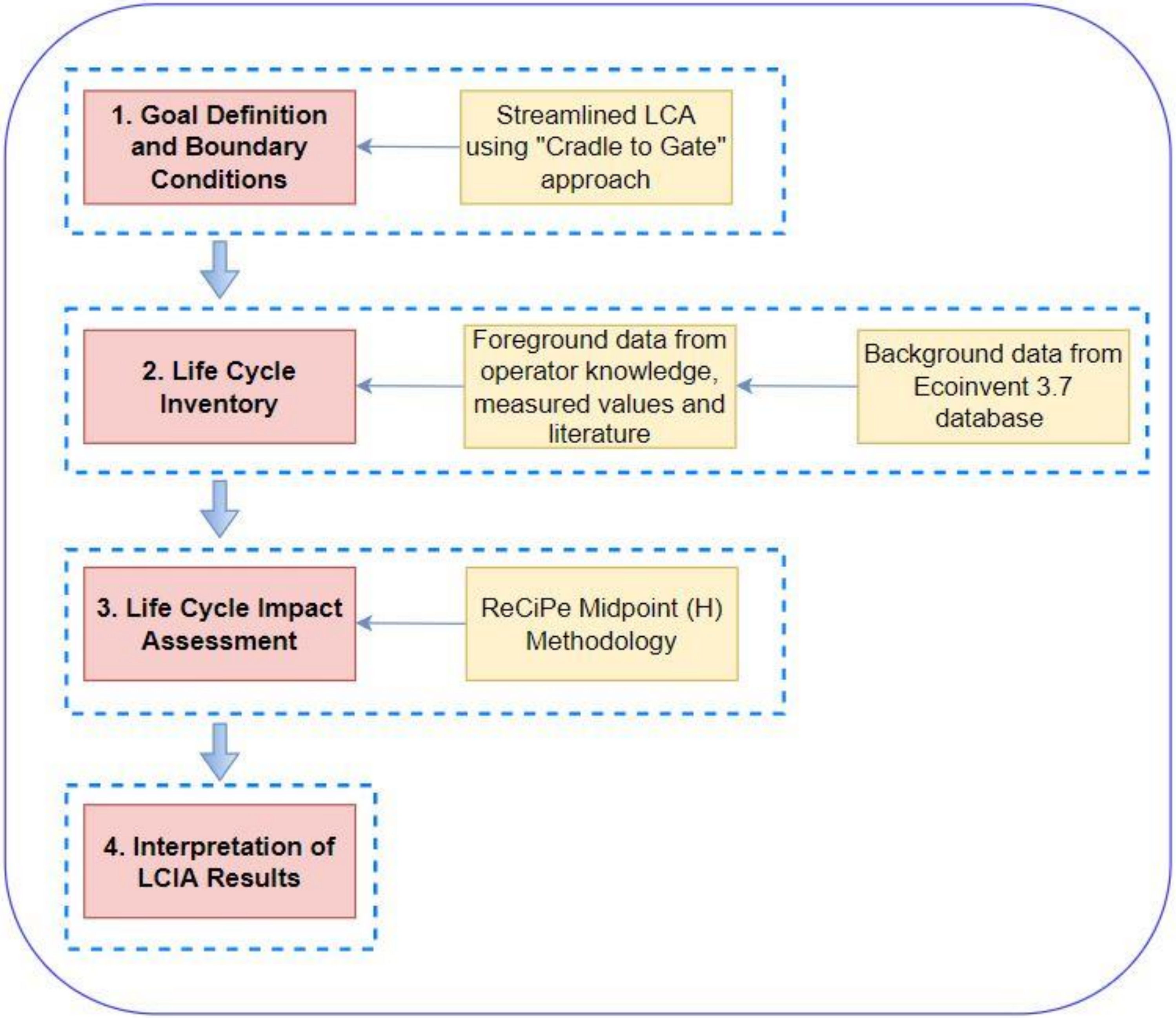

Figure 4

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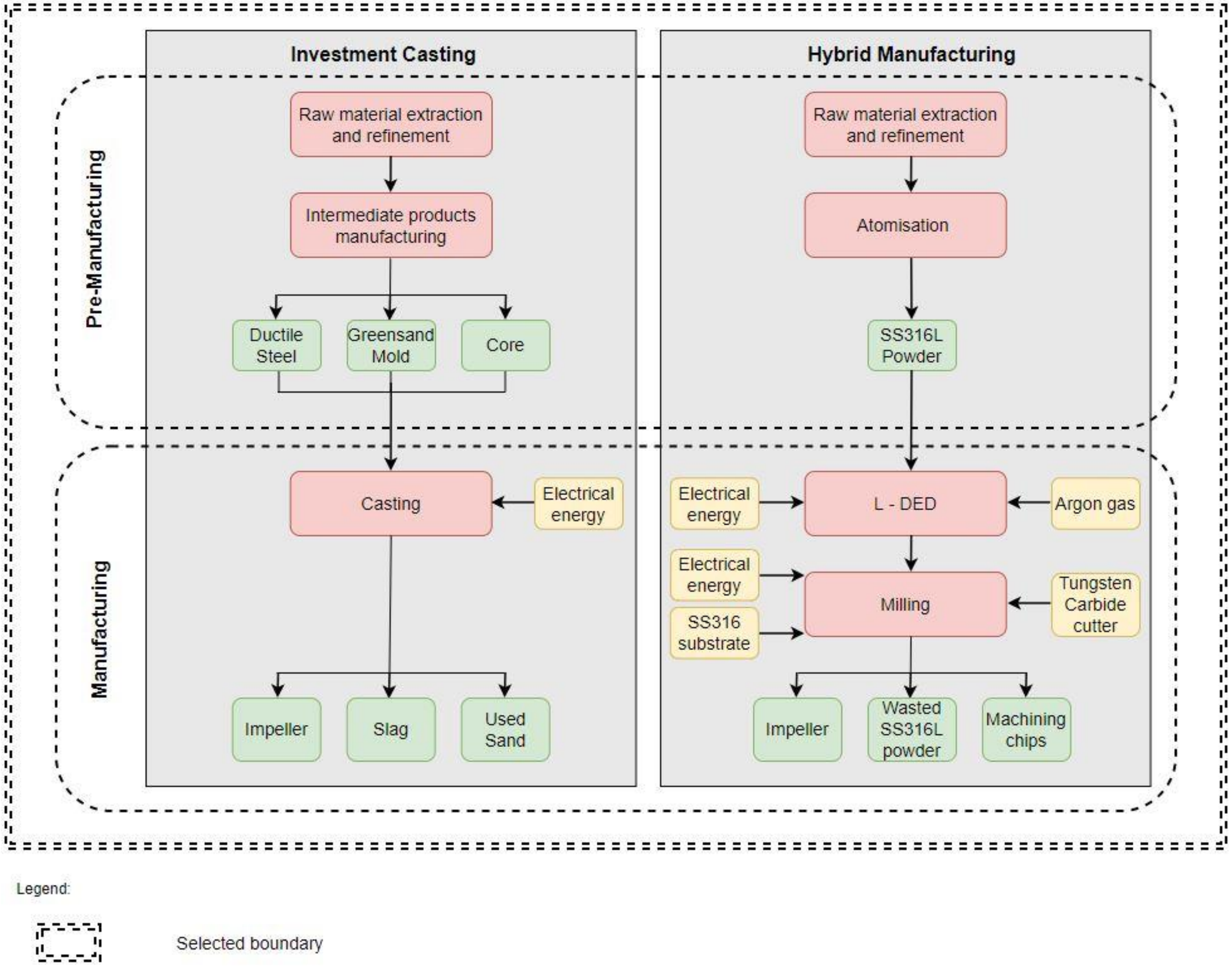

Figure 5

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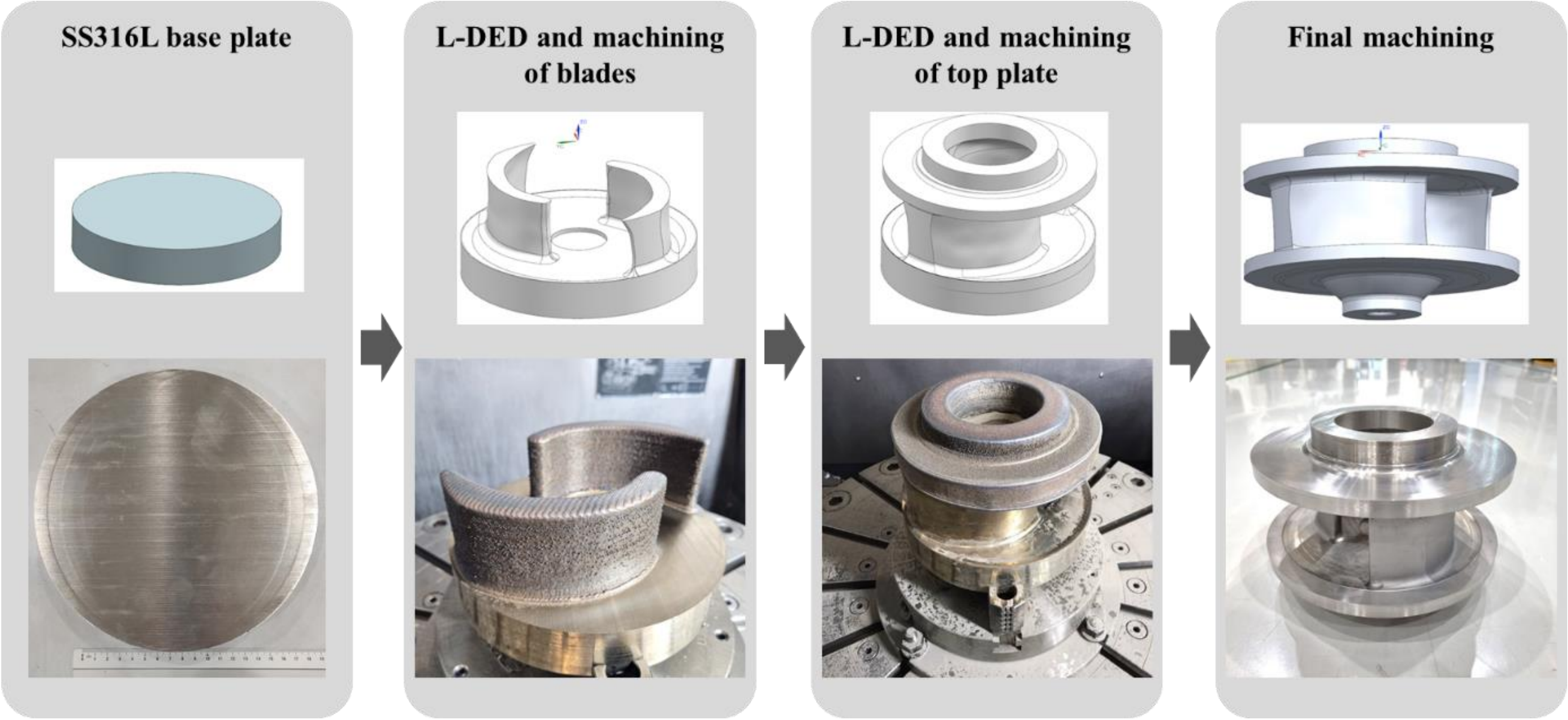

Figure 6

Figure 06

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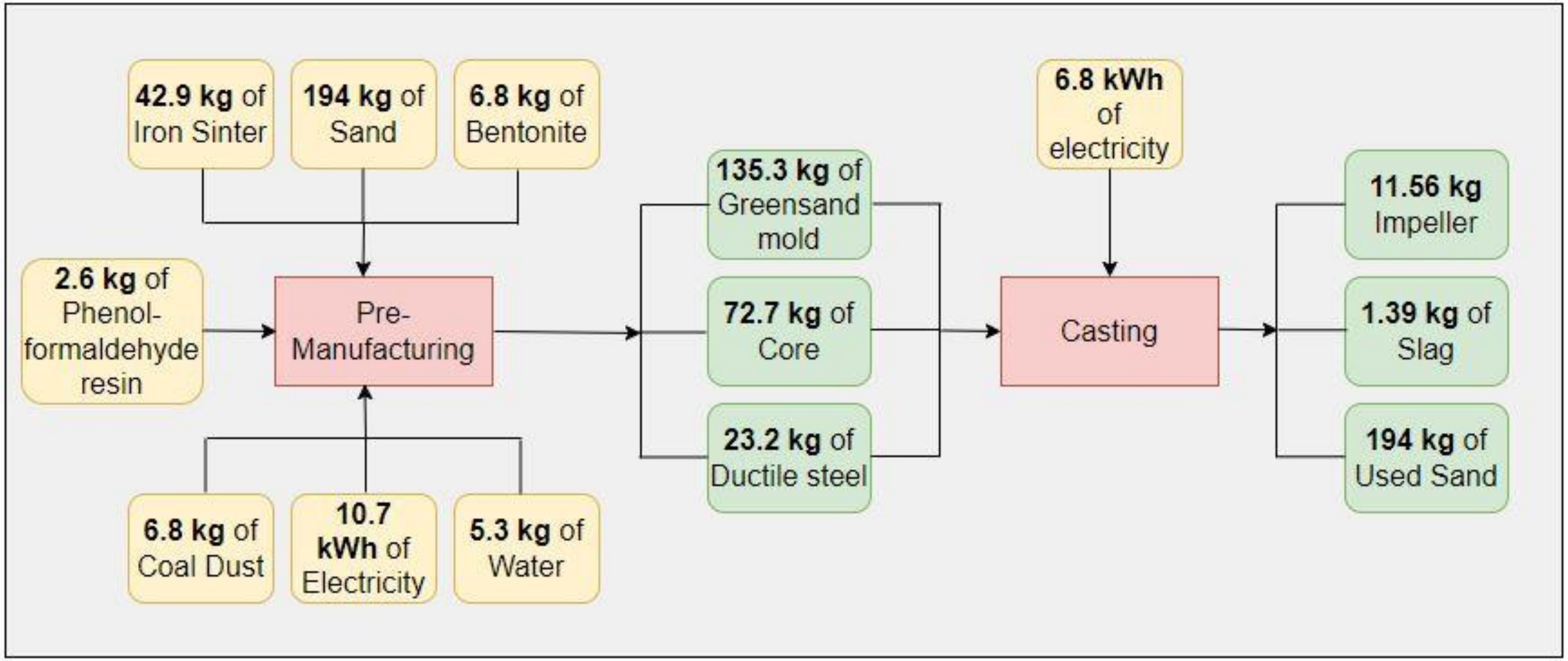

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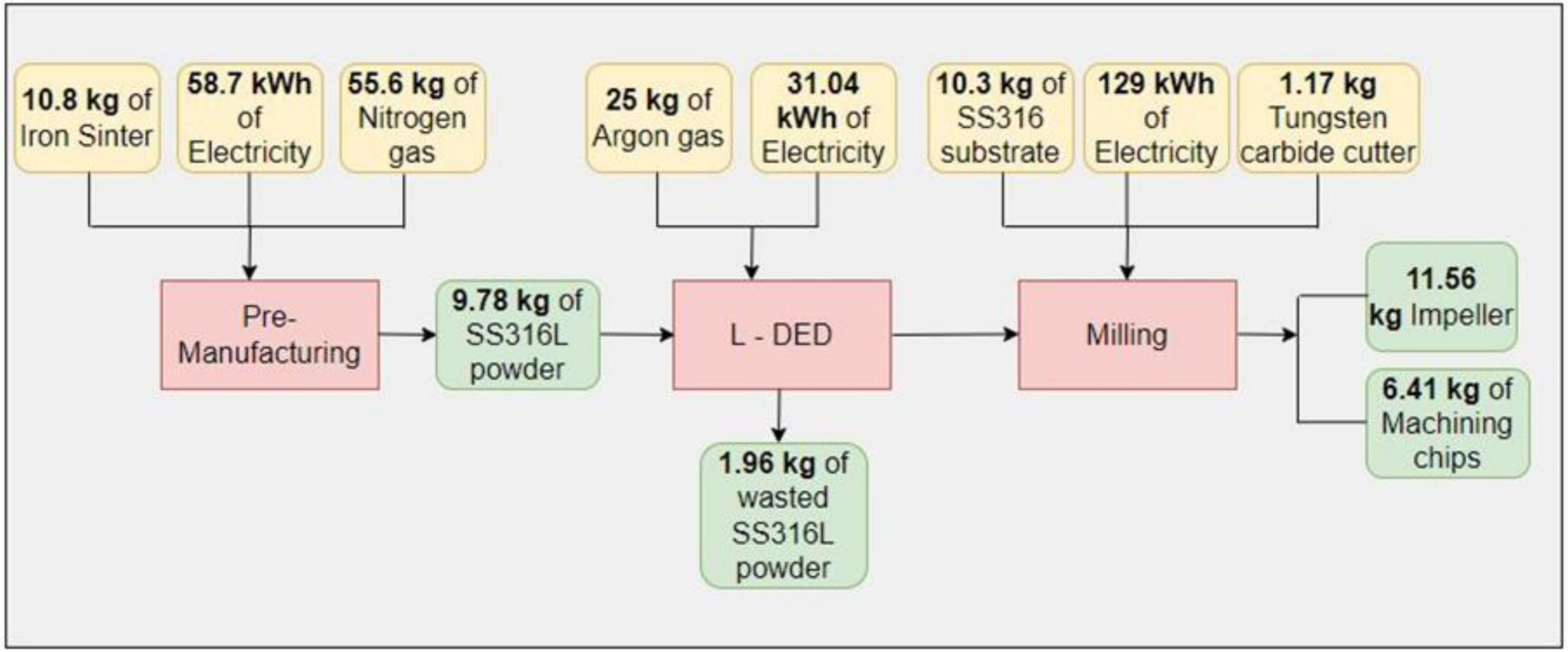
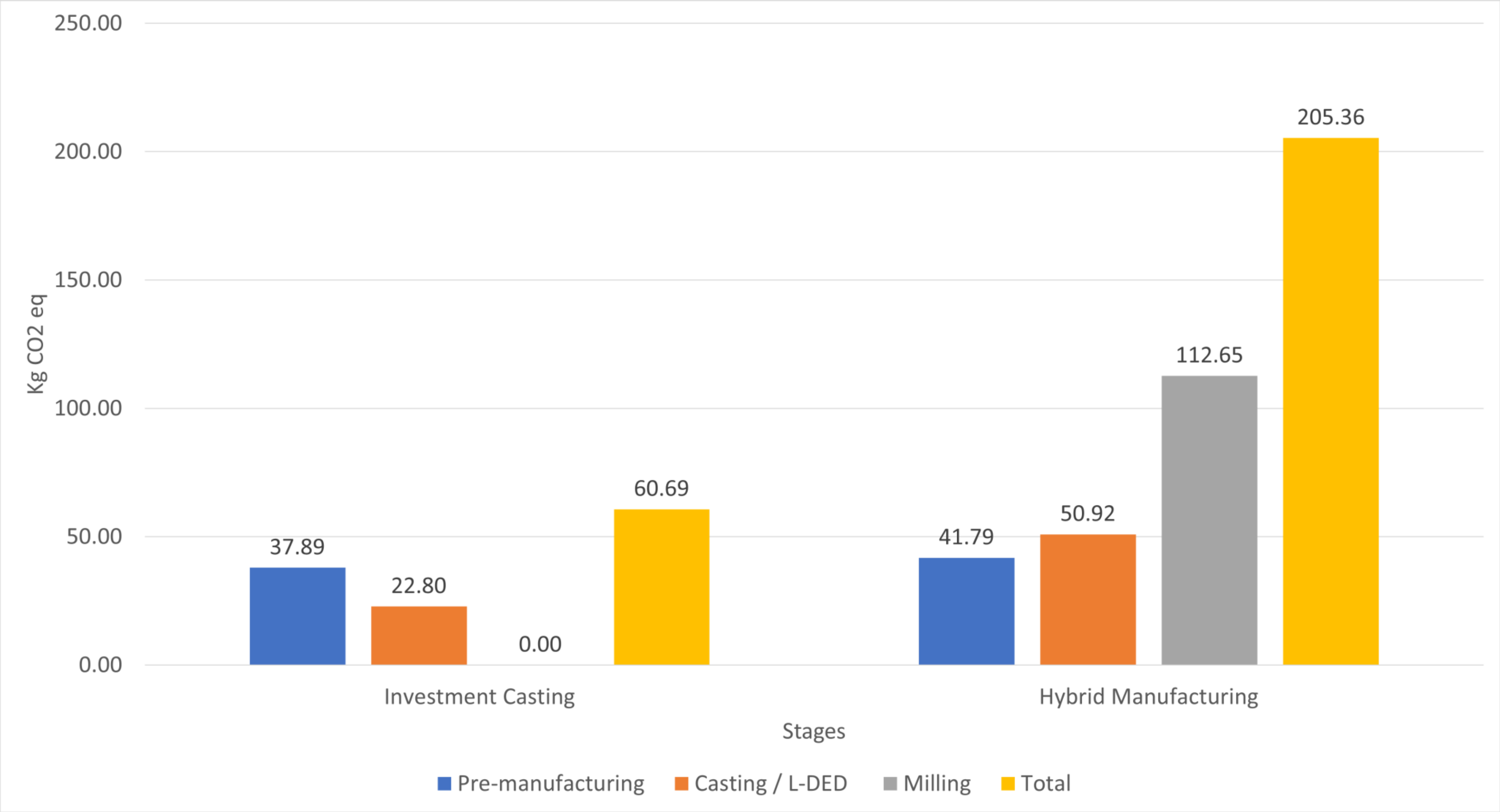


Figure 8

Figure 08



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Declaration of interests

☒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.

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CRediT author statement:

Davide Verdi: main investigator, conceptualisation, methodology, main author of the paper.

Joseph Joju: LCA analysis.

Aishah Larsen: hybrid manufacturing process, background analysis.

Guo Yong Chia: hybrid manufacturing process engineer.

Grace Tay: supervision of hybrid manufacturing process and final review of the paper.

Shan Shan Yang: final review of LCA and paper.

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With reference to your submitted paper, **<ID1129 - Environmental performance analysis of hybrid manufacturing of closed impellers>**, we are pleased to inform you that it has been accepted for presentation at the conference.

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