Present and Future Sustainability Development of 3D Metal Printing

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Abstract

Additive manufacturing (AM), also known as 3D printing is a relatively new concept and promising technology for industrial production. It is important to investigate the environmental impact of the AM process in light of the critical situation of the Earth. The elimination of some costly prefabrication processes such as molding or post-fabrication stages such as machining and welding required in traditional manufacturing methods favor the AM process and provide great economic advantages. Furthermore, the reduction of manufacturing steps contributes to environmental protection through fewer operations, less material, and energy consumption, and reduced transportation. This study is a preliminary work for analyses of environmental impact and life cycle of some well-known AM technologies for manufacturing metallic parts and components. As a case study, fabrication of a pump impeller is simulated through a well-known metal production AM technology and a conventional technology such as a casting process for direct comparison. Life Cycle Analysis (LCA) is applied to measure the environmental impact in five different stages of pump impeller lifetime with the two different fabrication processes. AM compared to casting has an environmental impact reduction of 15%, 20%, 65%, 20%, and 10% respectively in Global Warming Potential (GWP), Acidifications Potential (AP), Water Aquatic Eco-toxicity Potential (FAETP), Human Toxicity Potential (HTP), and Stratospheric Ozone Depletion (ODP). In the pre-manufacturing stage, the AM process has a higher impact on the environment in comparison with the casting process due to intense electricity consumption. Using hydroelectricity and renewable energy electricity mitigates the environmental impact of the AM process in pre-manufacturing and manufacturing stages as temporary until the advancement of AM technology for consuming less energy. Finally, a plan for future research to enhance the environmental sustainability of the AM process is proposed.

Keywords: *Metal Additive Manufacturing Sustainability; 3D Printing Life Cycle Analysis; Additive Manufacturing Environmental Impact; Casting Sustainability Analysis; Laser Metal Deposition Environmental Effect.*

1. Introduction

Innovative ideas demand a quick and inexpensive prototyping method to be competitive in the market. AM is a game changer and it started a revolution in the manufacturing industry [1]. Parts and components are fabricated layer by layer onto a build platform in AM technology. In metal printing, a heat source is used to melt feedstock powders for formation (deposition) of a layer which rapidly solidifies before deposition of the next layer [2]. Components with very complex geometries are manufactured using AM which are otherwise impossible to produce with conventional manufacturing methods [2]. Assemblies requiring several parts separately built and assembled are produced as one component using AM [2]. As manufacturing is shifted from conventional to AM, supply chains are expected to shorten due to reduced tooling requirements and localized production replacing centralized manufacturing [3], [4]. Another important characteristic of AM is the reduced likelihood of human error during manufacturing due to AM machines using digital computer aided design (CAD) files to provide the manufacturing specifications [5]. AM alters the design landscape by using digital CAD files which facilitate communication between design engineers and manufacturers, known as Direct Digital Manufacturing (DDM) [6]. DDM, with its ability to locally manufacture parts on demand from stored CAD files, reduces suppliers' demands that result in less transportation and ultimately less energy consumption and lower emissions [6].

The use of highly optimized tools and components produced using AM technology boost the efficiency of other manufacturing processes and allow the development of new hybrid processes. These hybrid processes lead to further customization of complex tooling that require fewer parts and assemblies, thus reduce the environmental burden [7]. This characteristic of AM alters business models by shifting the focus towards building durable, high-quality parts with less complexity to re-manufacture, such as a modular design that is easily upgradeable [7]. Having dedicated AM machine shops that handle large orders at once present the most economical and environmentally friendly scenario due to the machines being able to operate the maximum amount of time possible. AM machines that spend a majority of time idling waste significant amounts of energy and increases environmental concerns [8]. Comparison of low machine usage to high machine usage showed a lowering of environmental impact per component built by a factor of ten [8].

In general, AM process consume less energy which consequently results in reduction of CO_2 emissions of products with complex geometry over their life cycle. This characteristic of AM process has provided more liberty for designers, particularly for high value, low volume industries such as aerospace and medical [3]. Furthermore, AM has the potential to reduce economic costs by 170–593 billion US $ and the primary energy supply by 2.54–9.30 EJ and CO_2 emissions by 130.5–525.5 Mt by 2025 [3].

LCA are used to quantify the environmental effects of processes or products. Several LCA's regarding AM have been performed. Mami et al explored the environmental and economic aspects of AM in relation to the aeronautics sector [9]. They propose an approach based upon industries environmental targets and provide a recommendation for the eco-efficient application of AM technology. In their methodology, they derive a weighting factor between multiple normalized impact scored and the industries target goal. Conventional manufacturing of an aerospace component was compared with a normal AM process as well as a topology optimized AM component. They found that weight reduction (342 grams to 274 grams) from an optimized AM manufactured component made it the superior environmental technology.

Faludi et al extended the knowledge of AM environmental impacts by using an LCA to determine whether the environmental contributions of the raw material, printer hardware, or the process energy consumption was more influencing [10]. Their test specimen was a complex turbine manufactured using selective laser melting (SLM) with a cradle to cradle scope. They determined that electrical demands encompassed around 80% of embodied energy and around 66%-75% of the other environmental impact metrics. The electric demand was also sensitive to utilization rates of the machine, with more idle time resulting in more electrical energy.

Walachowicz et al. compared laser beam melting with traditional manufacturing methods (CNC machining) by repairing a burner for an industrial scale gas turbine [11]. They also explore recycling options on the environmental impact. They recorded the electricity consumption for the repair process as well as all other material flows. AM was found to be much more environmentally friendly due to its higher material efficiency. The conventional repair process wasted three times the mass of the AM repair process.

Turbine blades manufactured using SLM, Investment Casting and Precision Machining were compared via LCA by Torres-Carillo et al. [12]. Their investigation showed a decrease of CO_2 emissions from 7.32 tons to 7.02 tons by switching to the AM process.

Bekker and Verlinden performed an LCA of wire arc AM was compared to CNC milling and green sandcasting using stainless steel as the material [13]. They performed a cradle-to-gate LCA using empirical measurements of a wire and arc additive manufacturing (WAAM) process. The concluded that AM is equal to both the processes from an environmental standpoint when it has a 75% material utilization efficiency.

Böckin and Tillman performed an LCA using powder bed fusion technology for the automotive industry by considering a complete product lifecycle in comparison with conventional manufacturing [14]. They showeded weight reduction of an AM part played an important role during the use phase of the products, suggesting that lower weight products that produced using AM resulted in significant environmental benefits.

AM offers many potential benefits, however, the environmental effects need a complete investigation. This study presents the fundamental methods of the AM processes and describe different types of available AM technology with focus on exploration of environmental and economic aspects of the technology. Then, using LCA methodology, a comparative evaluation of a conventional manufacturing process and a well-known AM technology is investigated by fabrication of a metallic component. Fabrication of the case study part is simulated for both processes using open source data for the Life Cycle Inventory (LCI). Comparison of the LCA outcomes for two process is discussed and validated with other studies and methods for improving each process are suggested. Finally, future research for advancing the AM process are suggested with respect to environmental sustainability. The present work is an introduction for environmental sustainability examination of the AM process in general and is a foundation for future studies. The comprehensive sustainability inspection of different types of AM processes with actual experiments will be conducted by LCA to have the numerical values of environmental impacts.

2. Metal Additive Manufacturing

A 3D model developed by a CAD software is exported to the printing machine. This model is sliced into many individual layers to be fabricated during printing [2]. Different technologies can be used to form the product layer by layer according to the CAD model. Each technology has its own characteristics, advantages, disadvantages, and applications. Metal AM generally is compiled into three main categories [15]:

- powder bed systems (PBS),
- powder feed systems (PFS)
- wire feed systems (WFS)

These category identifications are not standardized in research and industry; however, the metal AM technology is the same among all methods. Proper energy input is essential for the success of the powders feed methods, since reduced part density in the form of voids appear in materials when the energy input during manufacturing is too low [2]. Conversely, too much energy input reduces density by entrapping gas within the part during the melting process [2]. In addition, surface quality of manufactured parts is essential to the success of many components. Factors for powders based systems that effect surface quality include the type of alloy, powders shape and size, energy source focal point size, and feed rates [16].

2.1. Powder Bed Systems

PBS construct components by raking a thin layer of metallic powder across a work surface and melting the powders in the specified geometry of the final solidified part [2]. Typical heat sources for melting powders are laser beams or electron beams. They require a support structure for heat dissipation as well as for the structure of the part [2]. The high levels of heat dissipation require pre-heating (200˚C-500˚C) of the bed in order to reduce warping [2]. In comparison to other metal AM processes, PBS build volume is less than 0.03 m^3, that results in limitation of the size of components [15].

PBS lasers have wavelengths of infra-red range with spot sizes between 50-180 μm, and laser beam melting (LBM) layer thicknesses are around 20-100 μm [2]. The choice of laser has significant impact on the quality of the product and it depends to absorptivity of materials for melting the desired powders sufficiently at given feed rate [17]. Inert gases such as Nitrogen or Argon are used to aid in keeping oxygen levels low for preventing any harmful chemical reactions [2].

2.2. Powder Feed Systems

PFS's utilize a nozzle to spray powders onto a surface to create the desired geometry instead of raking the powders across the surface like PBS [15]. As the powders are spayed, a heat source melts the powders similar to PBS [15]. The printing process is carried out by a raster motion of laser beam in a rectangular pattern across the stationary work piece [2]. Inert gasses in PFS are Helium and Argon to protect against oxidation [18].

PFS often have larger build volumes like the Optomec 850-R-unit of 1.2 m^3 compared to PBS [15]. Build rates of 300 cm^3/h (higher than PBS) are achieved using a layer thickness between 40 μm to 1 mm [2]. In addition to building new components PFS allows for rebuilding or repairing of existing products [15]. The subsets of PFS include [2]:

- Laser metal deposition (LMD)
- Electron beam melting
- Plasma arc beam melting.

The major focus of this research is on LMD. However, some other AM technologies have also been discussed in this study. A high-power laser source provides required energy for melting metallic powders in LMD process. There are many different aliases and commercialized variations of this technology such as direct metal deposition, laser direct casting, laser engineered net shaping, laser cladding, and laser deposition welding. These different names are adopted by various institutions and companies while they are essentially the same technology of using a laser to melt and deposit powders into a substrate [16].

2.3. Wire Feed Systems

WFS are extremely similar to PFS with a metallic wire instead of the metallic powders being the main difference [15]. Due to the large availability and low price of wire, WFS are less expensive than powder based systems [19]. WFS are capable of high build rates, associated with large molten pools, and large build volumes in comparison to PFS and PBS [19]. Because of rough surfaces, WFS often require post process machining to achieve the desired static and dynamic qualities [19]. WFS energy sources are divided into three subgroups like in PFS [20]:

- Electron beam based
- Laser beam based
- Electrical Arc based

The most common energy source for WFS technology is laser beam due to its high precision. However, it is an inefficient technology (2-5% efficiency) in terms of energy consumption. In comparison, the efficiency of electron beam sources are approximately 15-20% but it requires high vacuum working environments, which can limit its application [20]. Metal arc welding have considerably higher efficiencies than both laser beam and electron energy sources, sometimes reaching up to 90% [20]. However, higher accuracy of laser beam technology makes it more demanding instead of its lower efficiency.

3. Economics Aspects of Additive Manufacturing

Recent analysis of the market capabilities of AM predict that the AM industry will reach a market size of $50 billion between 2029 and 2031 and $100 billion by 2044 [21]. The majority of these markets are expected to be developed in the aerospace, automotive, and healthcare industries [22]. Additionally, it is expected that AM technology to highly implement in manufacturing of tools and molds with internal cooling by optimized channels that reduce thermal stress in loading dies which results in higher production rates [22]. As the technology further develops and penetrates the market, economies of scale have been found to be a reality, meaning that larger volume productions of materials using AM may be economically feasible [23]. AM is foreseen to rapidly alter the manufacturing market from manual engineer-to-order production, to a customer individual mass production market [24]. The implementation of AM into the market will integrate customers more closely to the manufacturers supply chain by reducing lead times, low volume products that would often take significant amounts of time to manufacture [24].

4. Environmental Aspects of Additive Manufacturing

4.1. Consumption Reduction

Compared to traditional methods in which material is removed from a larger block, AM fabrication is considerably less wasteful since parts are built layer by layer [5]. AM technology is more environmental friendly than traditional machining processes because little metal debris or chips are produced during fabrication process [25]. The majority (approximately 90%) of environmental impact in AM technology is a result of the atomization process required for feedstock powders manufacturing. The atomization process in powder manufacturing consumes high energy but results in small amounts of waste since it is a semi closed loop processing cycle [25].

The major sustainable benefits of utilization of AM technology are [5]:

- More efficient designed products
- Shorter supply chains, localized production, and condensed transportation routes.

Furthermore, these environmental advantages of AM technology have great impact on strengthening the local economy and social value [5].

The Solid Freeform Fabrication (SFF) and Direct Metal Deposition (DMD) as a die and mold manufacturing processes have high potential to drastically reduce conventional supply chain operations such as casting, forging, and machining, which results in dropping product lead times as well as the fossil fuel consumption, pollution, and resource wastes [26]. In a study by Morrow et al., three case studies considered: a simple injection mold insert, a mirror fixture, and a stamping die used in the auto industry for comparison of DMD and Computer Numerical Control (CNC) methods. The biggest defining parameter for energy consumption was the solid-to-volume cavity ratio, with low ratios tending to favor DMD processes while high ratios were more appropriate for CNC machining. The outcomes suggested that part geometry played a critical role in the comparison of the technologies, with more complex parts DMD is environmentally more favorable. For production of parts with low solid-to-cavity volume ratios, AM has been shown to be more efficient in terms of materials, time, and energy compared to milling process. Solid-to-cavity volume ratio is the ratio of component mass to the mass of the minimally bounding volume of the component assuming it is completely solid and composed of identical material as the component [26].

4.2. Resource Protection

Typical options for material disposal include recycling, re-using, repairing, or placing parts of the product in a landfill. Worldwide waste has been predicted to reach 2.2 billion tons by 2025, resulting in significant problems [27]. Unfortunately, despite expanded recycling networks, the human population has been increasing their resource consumption year over year [28]. One of the key advantages of AM is recycling capability of the product at the end of life (EOL). Recycling materials is crucial and has a huge impact on protecting resources as well as saving energy and water from reduced mining of new materials. Additionally, reducing waste allows the landfills to last longer. Practice for using recycled materials are as follows:

4.2.1. Recycled Powders

The material waste, emissions, and cost are reduced by using more recycled materials instead of unused original feedstock powders [29]. However, some studies have shown that the recycled powders can oftentimes contain incorrect particle sizes, which needed further refinement in order for the powders to be appropriate for re-use in fabrication [29]. In certain industries, particularly aerospace, the component demands high quality materials, which limits the use of re-used powders. Comparison between different manufacturing processes indicated that [29]:

- Approximately 87% of the materials in conventional manufacturing processes end up as waste while AM technologies such as LMD has almost no waste.
- A large amount (~70%) of waste powder from some manufacturing processes such as EBM cannot be re-used without proper treatment and recycling process.
- There is additional waste from the post processing due to material removal.

The average mass ratio of initial material to final product is reported to be in the range of 12:1 to 25:1 using traditional processes for manufacturing aerospace components made from titanium, while for AM processes this ratio is much lower, around 1.5:1 [29]. Furthermore, the use of topology optimization such as building honeycomb structures or internal cooling channels significantly cuts down on weight of components, which is particularly attractive for the aerospace industry [29]. However, the requirement of having a support structure to stabilize and fix objects during printing process may result in production of some waste materials during AM process. Currently, the possibility of proper recycling and reuse of support material is under investigation by industry [29].

4.2.2. Recycled Products

It is feasible to utilize both AM and traditional manufacturing technologies to take EOL parts and efficiently produce new parts in order to bypass the recycling stage. With this strategy, new products are fabricated from old products that possess similar mechanical properties of conventionally processed products [30]. Appropriate utilization of this approach can significantly reduce material and energy consumption during the manufacturing process [30]. Comparison between the primary energy usage of AM versus traditional manufacturing processes used in the refurbishing of EOL parts showed that the conventional repair process required significantly higher energy than the AM repair process, particularly in the amount of required materials.

5. Advantages and Disadvantages of Metal Additive Manufacturing

Application of AM technology to produce metallic parts and components exhibit many advantages over using traditional manufacturing techniques. Some of those advantages are small while others are considered game changers and have a significant effect on manufacturing of specific products. As with any revolutionary idea there are also some drawbacks that preclude AM from completely taking over and replacing traditional manufacturing processes. Many of these advantages and disadvantages are studied to either further their advancement or mitigate their weaknesses.

5.1. Advantages of metal Additive Manufacturing

- No significant tooling or molding process is required for AM process [5].

- Digital designs easily are shared and edited using modern CAD software [5].
- High rate of material recovery (approx. 97%) compared to traditional methods [18].
- Fabrication of highly complex geometries products that are not possible otherwise [18].
- When properly processed, static mechanical properties of metal AM materials are comparable to conventionally fabricated metallic components [15].
- Smaller and more localized supply chains leading to shorter lead times and less capital required [18].
- Opportunity for refurbishing of parts that would otherwise be un-repairable, such as turbine blades, bearing seals, and shafts [17].
- Multiple materials are deposited in a continuous spray within a single component, allowing for new hybrid material compositions [17].
- AM processes require no cutting fluids [31].
- Wear-resistant alloys are easily deposited onto tool surfaces that lead to a significant extension of useful life for metal tooling [26].
- AM allows for further use of aging products by building retrofits and extending operational life of equipment [32].

5.2. Disadvantages of metal Additive Manufacturing

- Low production volumes limits the technology only to be applicable for production of highly customized products that are expensive and difficult to manufacture via traditional methods [5].
- Microstructural and mechanical anisotropy results in weakened properties within the direction normal to the plane of deposition [15].
- Rapid heating and melting that negatively affect fatigue characteristics [15].
- Post-processing may require depending upon the requirements of the component [17].
- Low volume production makes mass producing items via AM difficult to achieve economies of scale [15].
- Intellectual property and copyright issues have potential to arise from the ability to easily distribute and share digital designs [24].
- High energy investment required to operate machinery [31].

6. Additive Manufacturing Sustainability Advancement

Although the field of metal processing via AM technology is relatively young, there is always effort to continually improve energy and materials efficiency for LMD technology. Various approaches are currently being researched with the goal of working towards enhancing AM technology, some are discussed below.

One of the drawbacks of LMD is the low energy efficiency. One method of increasing the efficiency is increasing the deposition speed by supplementing inductive assisted laser cladding [33]. Inductive heating is added to the laser process and compensates for rapid heat loss from the laser. The use of inductive heating during manufacturing increases deposition rates by a factor of approximately 2-2.5 while doubling the overall energy efficiency of the process [33]. Furthermore, adding the induction heat reduces spatial temperature gradients in the materials, which results in more durable structures.

The use of mechanical milling to produce feedstock powders for AM process makes it possible to develop a sustainable powders production route by making powders from a variety of materials chips with different sizes [34]. Due to the nature of mechanical milling, there is no requirement for high temperatures, which allows for significantly lower energy consumption in comparison to traditional atomization processes [34]. The powders are formed using a novel two-stage mechanical milling approach and have near-spherical morphology and particle diameters of 38–150 μm, making them comparable to conventionally produced powders [34].

The process chambers of the AM technology is improved with access to higher quality chamber seals, which reduces the consumed process gasses to generate the inert process atmosphere [35]. The accurate control of subsystems within the machine yields energy savings by turning off various parts of the machine in standby mode and downtime. A final design improvement is implemented a variable volume process chamber, where the height, width, and depth of the chamber adjusted to suit the requirement of the product for manufacturing and resulted in less energy consumption [35].

Efficient powders heating leads to less energy consumption. Improving laser technology results in efficiency increase of AM process, since lasers contribute to significant energy demand [36]. Consequently, using advanced lasers with high wall plug efficiency mitigates the significant energy consumption.

7. Life Cycle Assessment of Laser Metal Deposition

LCA as an essential tool for determining the environmental effects of a product or system and are commonly applied to evaluate sustainability. LCA’s were deemed important enough for an international code, ISO 14040, to be created to enable the practice of LCA’s within industry and research under a standardized method. LCAs is a tool for the analysis of effects of a process or product on the environment such as greenhouse gas emissions, ozone depletion, smog creation, eutrophication, acidification, depletion of resources, water use, land use, and many other aspects that are quantified and understood through impact assessments results from LCAs [37]. The four basic elements of LCA are the goal, scope, inventory analysis, and impact assessment. Interpretation of results follow the four basic elements and are defined for LMD machines in this study.

7.1. Case Study

The environmental aspects of manufacturing a stainless-steel pump impeller using LMD technology in comparison with casting method as a conventional process is the main goal of this section. The LCA is used as tool for this investigation with the functional unit being 1 produced pump impeller of a mass of 10.79 kg. The dimension and mass properties of the impeller are defined in Figure 1. While there are other aspects of both the AM and conventional process that are considered in this study. For simplicity several variables considered negligible for both process.

This LCA has a goal of demonstrating how the LCA process aids in identifying the environmental impacts of manufacturing the impeller via LMD processes in comparison to a conventional manufacturing process such as casting. The direct comparison of methods allows for the areas of greatest and smallest environmental impact to be identified for future improvement and understanding. By understanding the weaknesses and strengths of using LMD to replace casting processes, manufacturers of pump impellers and other similar products determine what manufacturing process yields the minimum environmental impact while still producing a high-quality component.

There are several unrestricted and commercial LCA Software packages with databases available such as GaBi, SimaPro, and openLCA. In this study, openLCA is used since its associated databases cover the presented case study. Although, the data sets in openLCA are based mainly for Europe, most of the data points are a global reference from the selected data sets [38].

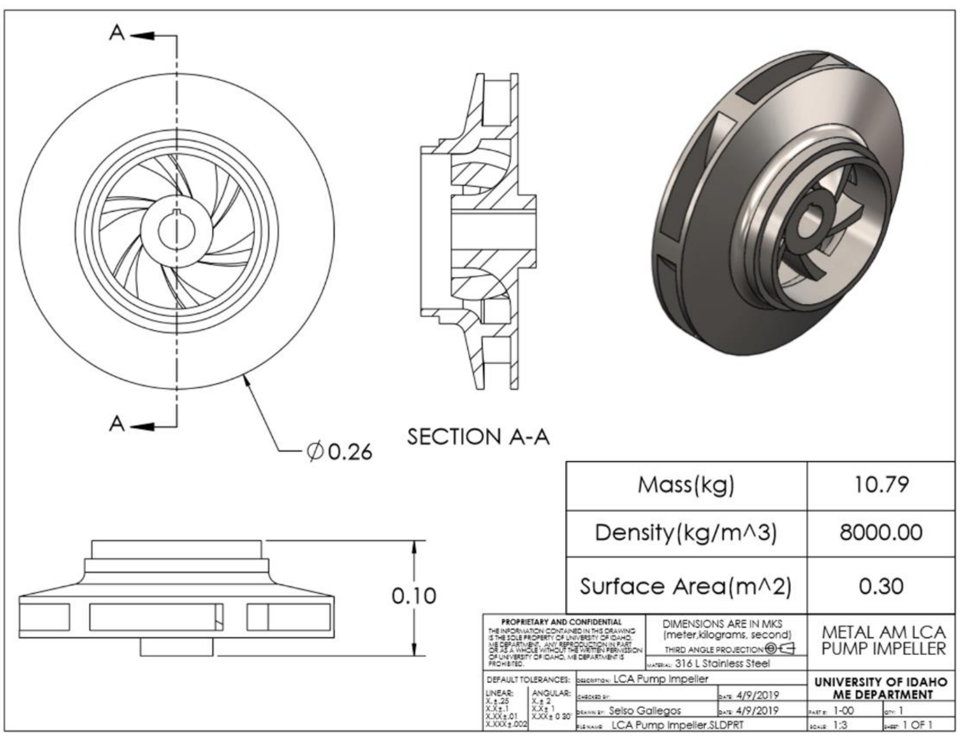

Figure 1: Drawing of pump impeller used for analysis

The aim of LCA is to quantify the consumed energy, released emissions, and environmental impacts of LMD manufactured impeller and casting manufactured impeller during 5 stages of pre-manufacturing, manufacturing, use, transportation, and EOL. The service stage of the impeller is not considered because the impeller rotation environmental impacts is negligible. Although, post processing sometimes is required in order to achieve a high-quality surface finish, it is not considered a requirement of the LMD process like it is for the casting process. GWP, AP, FAETP, HTP, and ODP are among the environmental impact indicators used to quantify the environmental impacts of the two processes.

7.2. Life Cycle Inventory

The LCI of the process is summarized in Figure 2 and Figure 3 for the LMD and Casting process for five different stages for the pump impeller.

7.2.1. Pre-Manufacturing

Generally, the pre-manufacturing stage of an LMD process includes mining and extraction of the raw materials in addition to the production of the metallic powders. a large variety of metals, including tool steel, stainless steel, titanium, titanium alloys, aluminum casting alloys, nickel-based superalloys, cobalt-chromium alloys, gold, and silver can be used as feedstock materials for LMD technology [39]. The mining and smelting of these materials has been fairly well documented and its environmental impacts are generally understood [40]. The environmental effects of mining are substantial and thus recycling materials should be strongly considered during the pre-manufacturing process due to economic and environmental considerations [41]. The powder formation process is generally referred to as the atomization process. The basic principle of the atomization process involves a stream of molten metal being rapidly disintegrated and cooled by a materials into individual particles [42]. Various techniques such as water, gas, centrifugal, vacuum, and ultrasonic atomization are used [42]. Water and gas atomization are the most common techniques used in industry [42]. Electrical energy is the major source utilized for heating materials in all pre-manufacturing techniques.

A couple of assumptions are required for better organization of the results:

First: the raw materials input for the powders atomization processes are sintered Iron (Fe) with a global reference value from the free Ecoinvent database on openLCA [43]. This data includes both material and energy requirements to obtain iron sinter. The materials efficiency for the atomization processes is assumed 90% efficient while the materials efficiency for the LMD manufacturing processes is also assumed 90% efficient. These values were estimated based upon values used in literature which were very high (95-98%), and so a more conservative 90% was thought to be more appropriate [11].

Second: the electricity and nitrogen gas required to produce 1 kg of steel powders is the same as required for titanium [45].

Table 1 summarizes the inputs used to model the Stainless-Steel atomization processes for the LMD case study. The casting process is estimated from Yilmaz et al. by scaling their inputs down in order to achieve the required 10.79 kg of steel impeller [46]. Their casting process is assumed to be the best available technology.

Table 1: Pump impeller pre-manufacturing inputs/outputs for LMD

Pre-Manufacturing LMD				
Input	Unit	Amount/Unit	Total Amount	Reference
Electricity (Atomization)	kWh	6.60	71.15	[45]
Nitrogen Gas	kg	5.17	67.46	[45]
Sinter	kg	13.04	13.04	[47]
Output	Unit	Amount/Unit	Total Amount	
Metallic Powders	kg	11.86	11.86	

Similarly, the inputs for the casting process are outlined in Table 2 for pump impeller.

Table 2: Pump impeller pre-manufacturing inputs/outputs for casting process estimated [46].

Pre-Manufacturing Casting		
Input	Unit	Total Amount
Sinter	kg	40
Electricity (mold making)	kWh	6.85
Electricity (core preparation)	kWh	3.2
Sand	kg	180.8
Bentonite	kg	6.3
Coal Dust	kg	6.3
Water	kg	4.85
Phenol-formaldehyde resin	kg	2.6
Output	Unit	Total Amount
Ductile Steel	kg	21.73
Greensand Mold	kg	126.3
Core	kg	67.9

7.2.2. Manufacturing

Generally, the most complex part of LMD process occurs during the manufacturing stage. In this stage, the primary energy inputs are required in the following parts of the process [48]:

1. Laser system.
2. Stepper motors for machine.
3. Pre-heating of work surface.
4. Other miscellaneous parameters such as computer, fans, and lighting.
5. Post processing.

The amount of energy required for manufacturing a part is depending upon the required machining time during manufacturing process. Time required is a function of process control parameters such as laser power, laser speed, scanning pattern, hatch spacing, particle feed rate, and idle time [49]. Typical laser size is on the order of 100-5000 W with beam diameters approximately around 1 mm in size [49]. Laser speeds are typically on the order to 1 to 20 mm/s and particle feed rates are in the range of 1 to 10 g/min [49]. Idle time is dependent upon the scanning pattern as well as the geometry and materials of the part and range from 0 to 1000 seconds, which results in a highly variable amount of energy expenditure.

Preheating of the work surface is used to reduce laser power requirements, improve radiation absorptivity of the powders and wettability of the substrate [50]. Typically, infrared or resistive heaters are used to heat the process chamber to temperatures ranging from 80˚C to 900˚C, depending on the materials used and desired component properties [50]. Much like the atomization process, gasses such as Argon or Nitrogen are typically used.

Post-processing is often required for LMD constructed parts in order to achieve the desired hardness or fatigue properties [51]. Annealing is often used which requires heat treatment for up to an hour at high temperatures. One of the benefits associated with LMD is the ability to recycle unused powders during the application process. Some sprayed powders onto the work piece do not melt by the laser beam during printing process. A large portion of the un-melted powders can be collected and reused for AM process. The recovery rate is estimated to be in the range of 95-98% for 3D printing of metallic materials [5].

Regarding the case study, Table 3 provides a summary of assumed variables used for the construction of the pump impeller. The mass efficiency of the powder process is assumed to be 90% [5]. Laser power is highly dependent upon build size, speed, material, as well as other parameters such as idle time. For this reason. The average laser power used by Faludi et al. were adapted due to the similarity in part size [10]. The average power consumed is 1 kW. The assumed particle feed rate (0.3 kg/h) [49] and powder mass (m = 11.86 kg) are used to calculate the time (t =39.53 hours) required to print the impeller.. The Nitrogen gas consumption is assumed the same as atomization process [45]. The electricity consumed by auxiliary heating requirements, stepper motors, lights etc. are neglected for the purpose and scope of this LCA.

Table 3: Pump impeller manufacturing inputs/outputs for LMD

Manufacturing				
Input	Unit	Amount/Unit	Total Amount	Reference
Electricity	kWh	1	39.53	[45]
Nitrogen Gas	kg	5.17	61.33	[45]
Metallic Powders	kg	11.86	11.86	[45]
Output	Unit	Amount/Unit	Total Amount	
Pump Impeller	kg	10.78	10.78	

Table 4 depicts the adapted inputs for the manufacturing phase of the casting process for pump impeller. The ductile steel produced from the pre-manufacturing stage is then melted and cast using electricity into the mold and core.

Table 4: Pump impeller manufacturing inputs/outputs for casting estimated [46].

Manufacturing		
Input	Unit	Total Amount
Ductile Steel	kg	21.73
Electricity (melting)	kWh	2.2
Electricity (casting)	kWh	4.1
Greensand Mold	kg	126.3
Core	kg	67.9
Output	Unit	Total Amount
Good Casting	kg	10.79
Slag	kg	1.3
Used Sand	kg	180.8

7.2.3. Use (Service condition)

The application or service of a product or process should include all the energy and materials input plus emissions related to scope of the LCA. The scope definition of the project determines intensity of the product use investigation. When comparing two different products or processes, it is possible the product resulting from one process performs inherently better than another during its useful lifetime. Those results are considered when substantial information is available to accurately quantify the effect of the improved performance.

In this study, an LMD process yields a pump impeller that resulted in a well-documented improved efficiency over the same pump impeller manufactured from traditional methods. The effect is included in the use section. However, there is likely to be a great deal of uncertainty in obtaining the quantities required for analysis. In most cases, an uncertainty factor is included in processes to specify that a parameter is not 100% correct. LMD is used to repair and extend the life of components [49]. By extending the life of a component, the environmental impact resulting from replacement of the impeller is reduced over time by avoiding the manufacturing of a new impeller. Essentially, it is assumed that there is no impact from the service stage based on the quality of the LMD and casting manufactured impellers are similar enough that there is no change in operating efficiency of the impeller during use. Assuming constant quality eliminates the need to estimate two type of wearing for 3D printed and casted impellers over the operation.

7.2.4. Transportation

The effect of transportation for any process varies widely depending upon the required distances between various stages in the product or process lifecycle. Typical transportation processes involve several stages.

1. Raw materials from location of extraction to pre-manufacturing facility.
2. Pre-manufacturing to manufacturing facility.
3. Manufacturing facility to distribution center for product.
4. Shipping to customer.
5. Disposal to landfill site, recycling center, and/or repair facility.

One of the potential benefits of metal AM is its ability to allow for smaller supply chains [18]. Through AM process the number of stages in the traditional supply chain is reduced by redesigning/designing products with fewer components and manufacturing products near the consumers [31]. Powders production is accomplished using locally sourced recycled materials, thus eliminating the need for shipping materials extended distances. The LMD manufacturing facilities are constructed near atomization facilities to further limit transportation environmental effects. Therefore, five stages of transportation reduce in LMD manufacturing.

In this study, transportation parameters for the pump impeller are summarized in Table 5. Both the LMD and casting process are assumed to experience similar transportation needs, and thus Table 5 is applicable for both processes. They are broken down into the type of shipping and life cycle. Due to the fact that majority of the data sets used in the LCA originate from Europe, the LCA and the parameters for transportation are based out of locations in Europe. Between pre-manufacturing and manufacturing, the feedstock metallic powder travels approximately 400km via ship from Town Castle, United Kingdom to Bremerhaven, Germany. After the part is manufactured in Bremerhaven, it transports via train 504km to Frankfurt, Germany where it is implemented. Once the impeller reaches its EOL it ships via truck for 225 km from Frankfurt, Germany for recycling.

Table 5: Pump Impeller Transportation for LMD and casting processes

Transportation				
Transport Method	LCA Phase	Cargo(kg)	Distance(km)	Reference
Ship	Pre-Manufacturing to Manufacturing	11.86	400.00	[52]
Train	Manufacturing to Use	13.04	504.00	[52]
Truck	Use to EOL	10.78	225.00	[52]

7.2.5. End of Life

Since LMD utilizes metal powders as the feedstock materials, there are typically many avenues available for recycling metal powders [53]. Due to economic incentives, the recycling of valuable metals [54] as well as electronic waste [47] are receiving many attention. The goal of recycling within AM is often to create a closed loop product life cycle, wherein the product materials at the EOL is completely recovered for use in other products.

The different metallic wastes and scraps are split into several categories, each representing a portion of the product lifecycle, although there is no scrap in LMD process. Home scrap represents the materials waste generated during manufacturing that is directly inserted back into the process [53]. For metal AM, this would be the powders waste from one build being reused into another process. New scrap refers to manufacturing waste of materials that have known properties and known value that is not recycled within the process but instead shipped to another facility [53]. Due to the majority of powders being recycled within the product production chain, the amount of new waste generated from metal AM is likely negligible. Old scrap is materials that has reached the product EOL, and generally requires more energy input to recover [53]. Functional recycling is used when old scrap is separated easily and combined with old scrap of similar composition to create new metal in the same family of materials [53].

In this study, when the pump impeller reaches its EOL, it is recycled back into powders that would be used to for another Stainless-Steel part made by LMD. The amount of energy required to recycle 1 kg of Stainless Steel is 7.96 kWh [44]. It is assumed that 90% of the impeller is recovered and turned back into stainless steel powder. The amount of nitrogen gas and electricity required for atomization of the recycled steel is assumed the same as what is used in the pre-manufacturing phase.

Table 6: Pump impeller EOL inputs/outputs for LMD

EOL				
Input	Unit	Amount/Unit	Total Amount	Reference
Steel Impeller	kg	1	10.78	
Electricity (Atomization)	kWh	6.60	64.03	[45]
Nitrogen Gas	kg	5.17	55.74	[45]
Output	Unit	Amount/Unit	Total Amount	
Metallic Powders	kg	9.70	9.70	

Table 6 outlines the inputs and outputs for the recycling process of the LMD while Table 7 indicates EOL process for the casting operation, which was estimated from [46]. The cast impeller is also recycled in a similar way, since both processes are composed of steel. The used sand is partially recovered since these can be re-used within the process. From literature, it is usually assumed that around 90% of sand can be recovered [55]. The values in table 7 are for a 90% recovery of steel and its sand. Further sensitivity analysis is provided to explore the effects of recycling rate on EOL impact.

Table 7: Pump impeller EOL inputs/outputs for casting

EOL		
Input	Unit	Total Amount
Electricity (Recycling)	kWh	85.8
Used Sand	kg	180.8
Steel Impeller	kg	10.79
Output	Unit	Total Amount
Recycled Sand	kg	162.7
Recycled Steel	kg	9.7

Figures 2 and 3 iluustrate the LMD and casting processes in different stages of life, used for LCA. These figures show energy and materials flow in both LMD and casting processes for impleller fabrication.

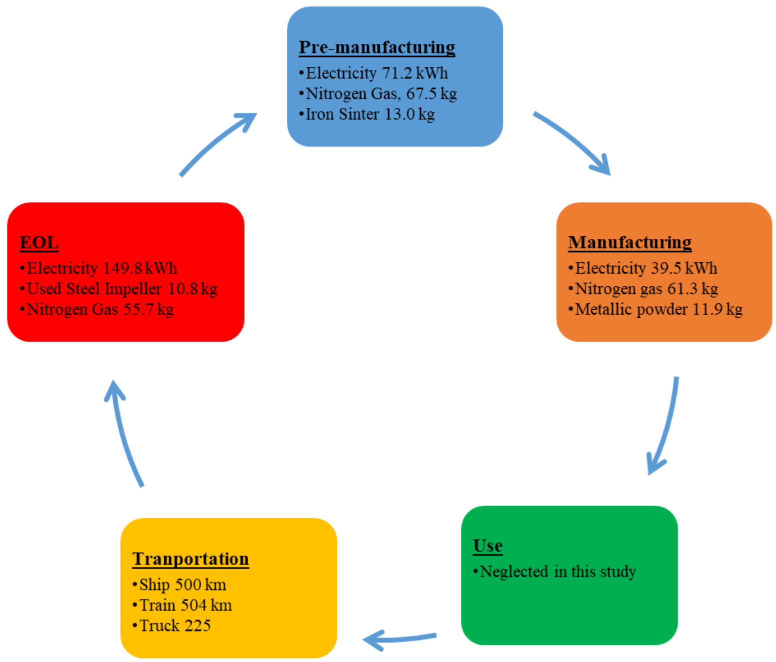

Figure 2: Summary of inputs for each stage of the LMD process

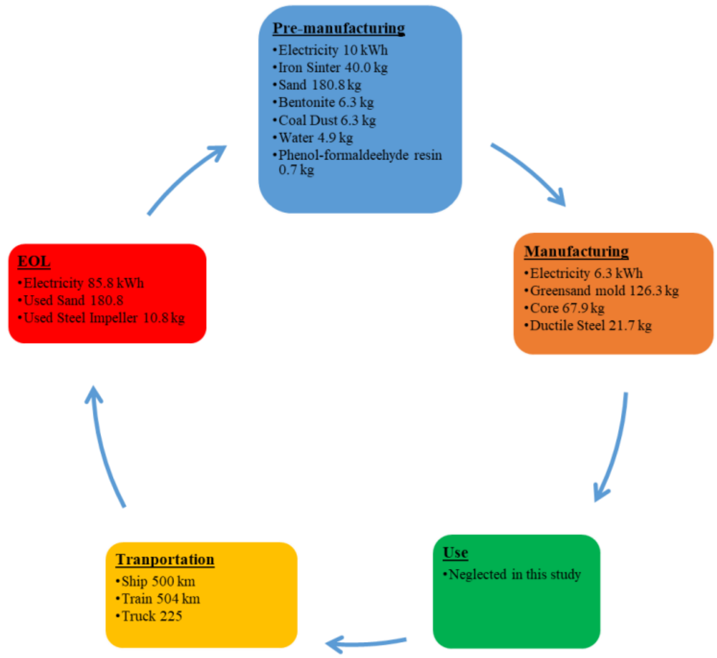

Figure 3: Summary of life cycle inputs for casting process

7.3. Impact Analysis

The goal of Life Cycle Impact Assessment (LCIA) methods is to connect each LCI result to the selected environmental impacts [56]. Each LCI result will affect the impact category and feed the overall LCA result. LCIAs should follow the definition and guidelines outlined in the ISO 14040 Standard. International standard ISO 14042 provides guidance for application of the LCIA [57].

The climate change potential is measured in kg of CO_2 emissions released directly or indirectly throughout the life stages of the product. It is commonly known as the Carbon Footprint or GWP of a process [58]. Analyzing the GWP is important because it is direct measure the climate change impact a process has on the environment [59]. The Acidification Potential (AP) is a measure of kg of SO_2 released into the environment by a process. AP is described as the soil and water destruction via acid rain caused by acidic air emissions released into the environment [60]. FWEP analyzes the environmental impact on fresh water ecosystems caused by toxic substance emissions to the soil water and air [61]. HTP is a measure of the potential harm a chemical emission has on the environment [61]. FWEP and HTP are measured in kg of one, 4-Dichlorobenzene (1,4DCB). One, 4DCB is an organic compound found in the atmosphere that has been classified by the EPA as a possible carcinogen that has detrimental impacts to the environment [62]. ODP is measured in kg of Chlorofluorocarbon (CFC), which is an organic compound produced as a by-product in different manufacturing processes [63]. It is composed of chlorine, carbon, and fluorine needs to evaluate because its' impacts are catastrophic to the environment [63]. CFC reacts with oxygen in the atmosphere and diminishes the ozone layer of the atmosphere in turn allowing more solar ultraviolet radiation to enter the atmosphere which impacts biological activity on the Earth's surface [63] like increasing skin cancer rates.

The Ecoinvent database developed by the Swiss Centre for LCI is used for impact analysis in this study [52]. CML 2001 is an operational guide for the ISO standards that provides impact categories and classification methods for an LCIA [43]. CML 2001 impact assessment method links the elementary flows of the Ecoinvent data to the characterization factors selected in the openLCA software project.

For this case study, CML 2001, Ecoinvent database, and openLCA are applied to quantify the impact categories. Table 8 provides an overview of the impact categories designated for the pump impeller case study impact assessment [43]. The impact categories are selected based on the most common environmental impact parameters.

Table 8: Pump Impeller Impact Categories

CML 2001 Impact Categories Implemented in Ecoinvent Database		
Impact Categories	Name	Unit
Climate Change	Upper Limit of Net GWP	kg CO2-Eq
Acidification Potential	Generic	kg SO2-Eq
Freshwater Aquatic Ecotoxicity	FAETP 100a	kg 1,4-DCB-Eq
Human Toxicity	HTP 100a	kg 1,4-DCB-Eq
Stratospheric Ozone Depletion	ODP 10a	kg CFC-1-Eq

7.4. Interpretation of Results

The overall GWP for the pump impeller of case study is 3.21 and 3.78 kg of CO_2 for the LMD process and the casting process respectively. This represents a 15% reduction of CO_2 by LMD process in comparison with casting process. Figure 4 shows the breakdown of the GWP of each life stage of the pump impeller.

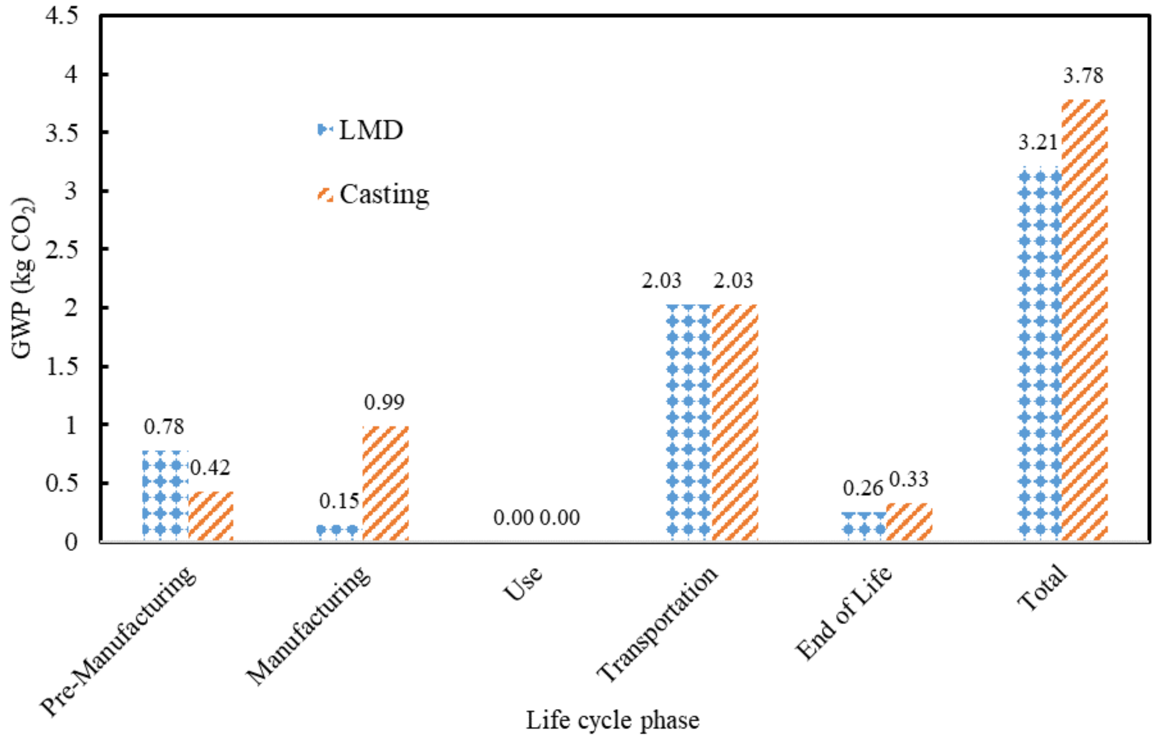

Figure 4: LMD and casting processes GWP comparison

For the LMD process, the transportation contributes the most CO_2 to the GWP, which is equal to casting. In pre-manufacturing stage, LMD consumes more electrical energy compared to casting. This is due to the high SEC required for powder production. LMD process performs better in the manufacturing stage, likely a result of the significant energy required for melting and casting as well as the significant amount of waste.. In the last stage of EOL both processes show the benefits of recyclability, while the LMD process is superior.

The AP of LMD and casting are depicted in Figure 5. Similar to GWP, the pre-manufacturing process for LMD has significantly higher AP than the casting due to the high-energy requirement. The manufacturing stage for casting contains much higher acidification potential resulting from the output waste of the mold and cores. On contrary, LMD process is more sustainable than casting at EOL stage. In total, LMD process contributes 20% less to AP than casting.

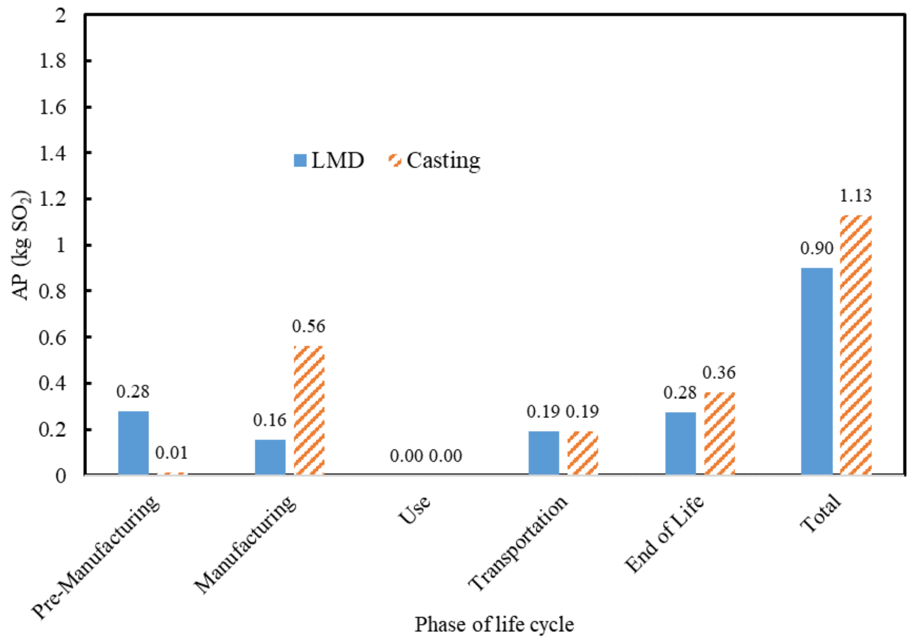

Figure 5: Acidification potential of LMD and casting processes

FAETP is illustrated for LMD and casting processes during each life stage in Figure 6. In the pre-manufacturing stage, casting has higher impact on FAETP because of sand molding process. Casting FAETP during the manufacturing phase is also much higher than LMD as a result of the significant amount of waste. Overall, LMD process has 65% less contribution on FAETP than casting.

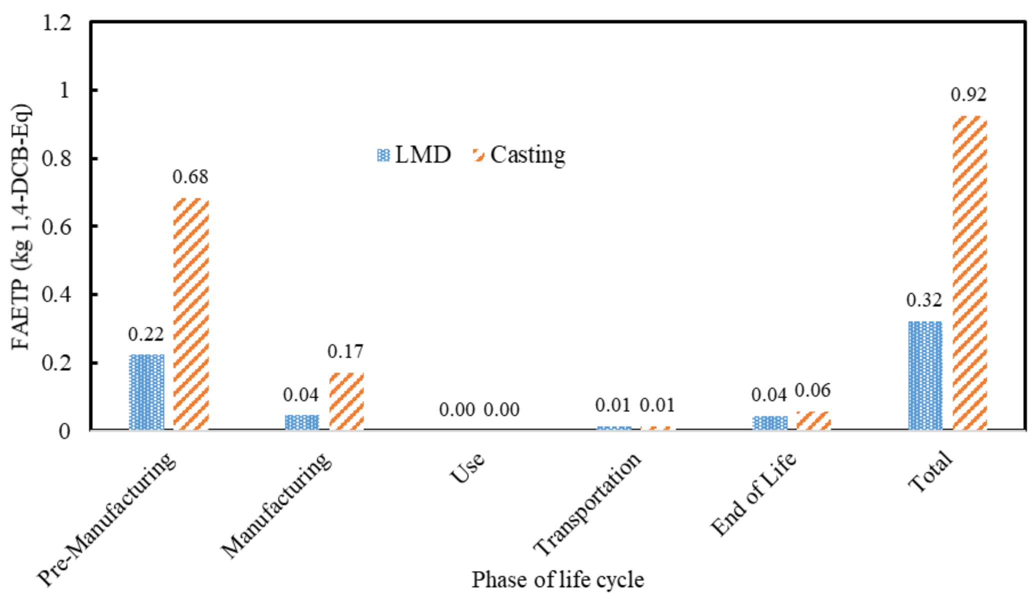

Figure 6: FAETP comparison between LMD and casting processes

HTP for LMD and casting processes in different life stages are shown in Figure 7. The LMD process shows the greatest quantity of HTP in the pre-manufacturing stage, followed by the EOL stage, because of high electricity consumption required for atomization. The casting process, with its required greensand molds, suffered in the manufacturing process. Transportation has the lowest effect on HTP. Generally, LMD process cause 20% less impact on HTP in comparison with the casting process.

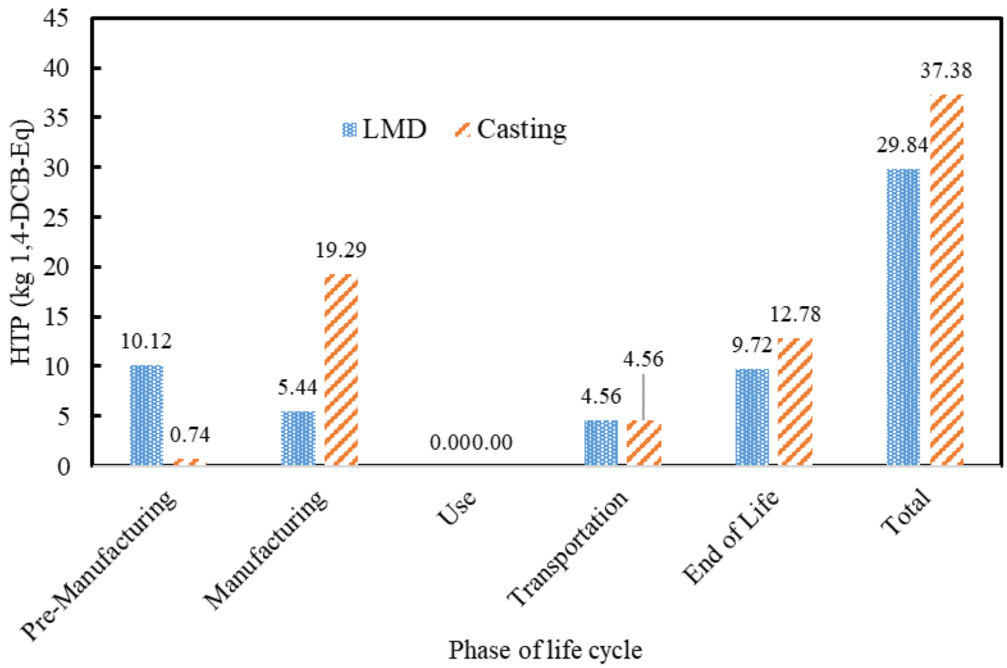

Figure 7: HTP for both LMD and casting processes

Figure 8 presents that ODP of LMD and casting processes in various stages. In pre-manufacturing stage, LMD has higher effect on ODP than the casting. While at the manufacturing stage, the LMD has much less impact on ODP than casting. It concludes that LMD has 10% less impact on ODP in comparison to casting.

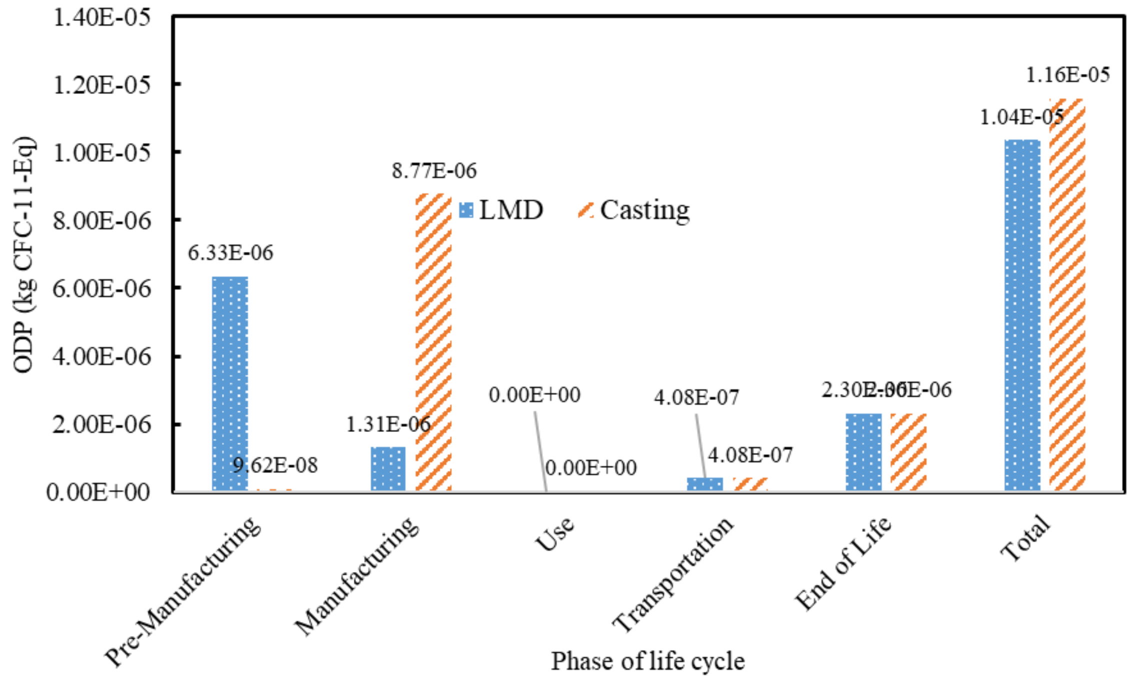

Figure 8: Ozone depletion potential for LMD and casting processes

8. Validation

Since online data was used for the case study, other similar case studies were investigated to validate the outcomes of the study. Peng et al. conducted an experiment for fabrication of an impeller applied in turbomachines with different production methods including AM and casting processes [64]. Their results showed that the environmental impact through indicators of GWP, AP, Chinese resource depletion potential (CADP), and respiratory inorganics (RI) were much lower in AM process in comparison with casting. Table 9 compares the findings from this study with the one reported by Peng et al. for AM processed case studies.

When taking into account the variability of many different parameters in the LMD process, such as build rate, powder size, SEC of powder consumption, and materials utilization efficiency, the authors believe the results of the case study presented in this study are in acceptable agreement with the similar studies.

Table 9: Results comparison

	Built Rate (kg/h)	Laser (kW)	SEC (kWh/kg)	Powder Efficiency (%)	Environmental Impact Indicators	Outcome
This study	0.3	1	6.6	90	GWP, AP, FAETP, HTP, ODP	AM Superior
Peng et al.	0.47	1	0.6	92.5	GWP, AP, CADP, RI	AM Superior

9. Discussion of the Results

To depict picture complete portrait of the AM process, the advantages and disadvantages are compared to a conventional casting process. Manufacturing a pump impeller was considered as the case study while principles of LCA were used to quantify the environmental effects. Prior to discuss the numerical value of LCA in each process, it should be mentioned that the AM process and casting are closed cycle process from the point of material recyclability as depicted in Figures 2 and 3. The simulations concluded that LMD environmentally is more sustainable than casting process. Figure 9 illustrates the percentage reduction of LMD compared casting in GWP, AP, FAETP, HTP, and ODP.

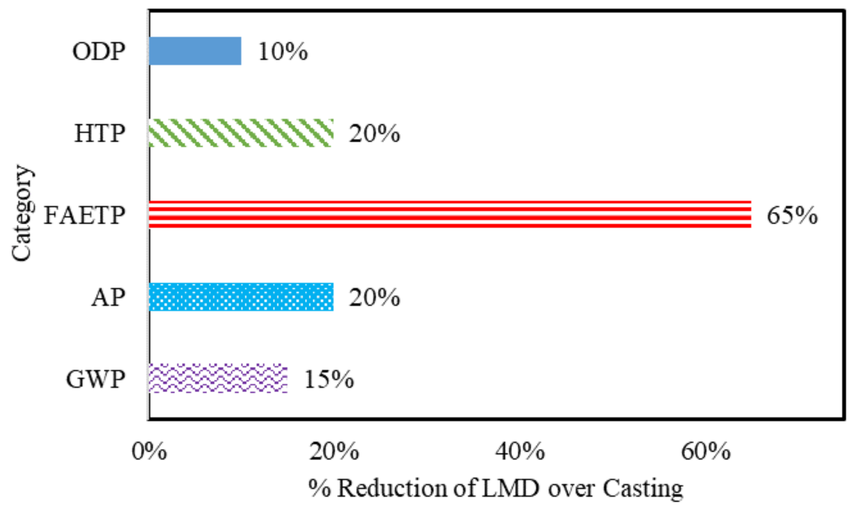

Figure 9: Summary of LMD environmental impact reduction over the casting process

The intense electricity consumption during the atomization process of powders in pre-manufacturing stage make LMD less attractive in comparison to casting process during this stage. In the other stages, however there was a strong indication that LMD is more environmentally friendly. For further improvement, authors suggest using electricity generated from renewable energy resources and hydroelectricity to lessen the environmental impact of the LMD on the environment during pre-manufacturing, manufacturing and EOL. However, this is not the ultimate solution for improving the LMD process. Finding new methods to lower electricity demand as well as achieve higher build-up rates for the manufacturing stage are permanents solutions for enhancing the LMD.

The size of the laser and build-up rate of the machine depend on the manufacturer, and therefore, it accounts for a large change in total energy required for the manufacturing process. The large difference in SEC for the powder production is an interesting fact. The build-up rate, powder size, SEC of powder consumption, powder type, and powder utilization efficiency influence the LCA of the AM process. In particular, the SEC of the atomization process was found to be highly variable. 6.60 kWh/kg was used for this LCA, yet in literature it is reported as a range for steel from 4.2 kWh/kg to 7.2 kWh/kg [65].

Finding the impact of different recycling rates in the EOL stage for both casting and LMD were performed as part of a sensitivity analysis. Recycling rates of 50% and 70% are shown in

Figure 10 for both processes. The values indicate the increased GWP resulting from additional virgin resources being required to make up for the decreased recycling rates. For example, a 70% recycling rate would result in an increase of GWP of 0.08 for the LMD process since the required material would have to be obtained from the pre-manufacturing process again.

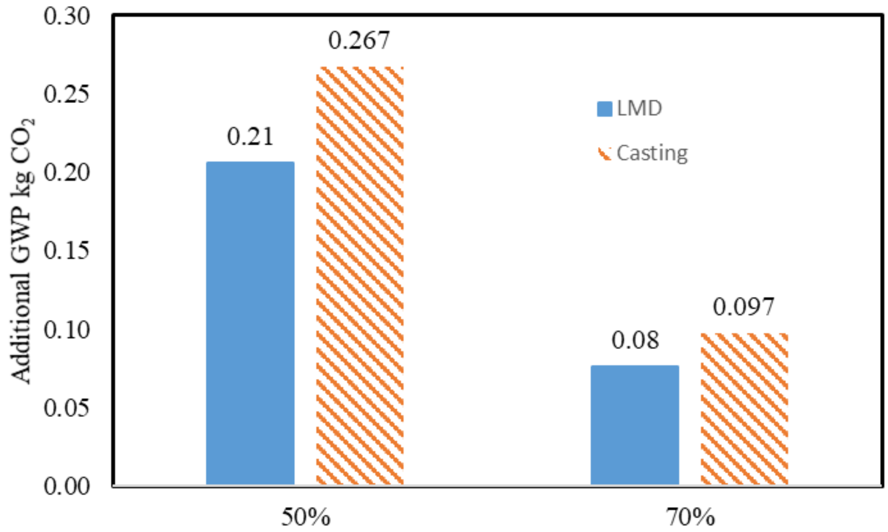

Figure 10: GWP increases resulting from decrease d recycling rates.

A similar sensitivity analysis on the average laser power shows increased GWP if the average power is increased. Figure 11 shows the total GWP if the laser power is 1 kW, 1.5 kW, or 2 kW.

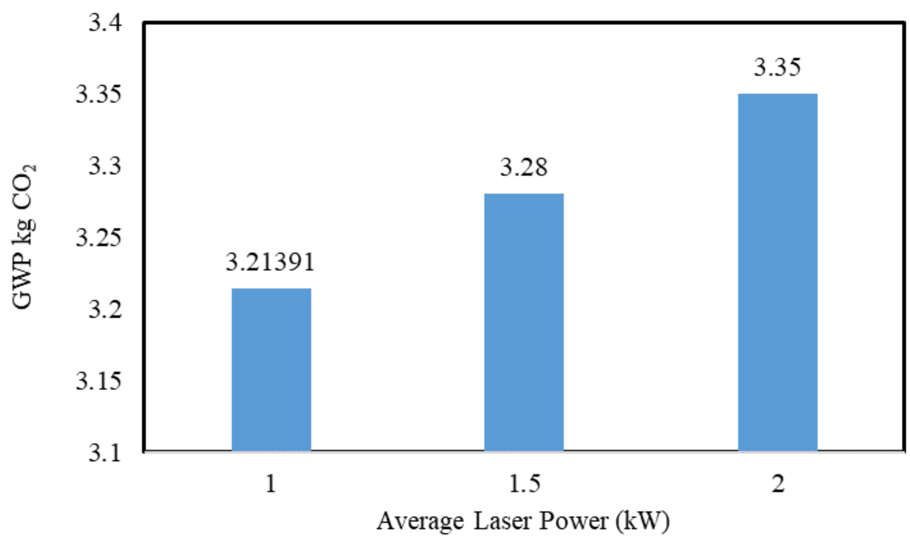

Figure 11: Average laser power and GWP.

10. Conclusions

The field of AM is growing rapidly, and modern fabrication is trending towards a revolution. Due to the potential environmental impacts resulting from AM, the effects of the process need more investigation. This study presented an overview of fundamental technology used to fabricate AM metal parts, followed by environmental and economic advantages of AM. There is no need for expensive molding or different stages of machining in the AM process, which presents a great economical advantage while lowering harmful contribution to the environment through fewer operations, less materials and reduced transportation. The most desirable characteristics of AM process are its recyclability, possibility of reusing feedstock materials, and its high material efficiency. Recycling the waste powders during the AM process and at EOL make AM an attractive technology. The drawbacks of AM have also been presented to show a more realistic picture of the AM process. To compare the AM process with the conventional processes, the fabrication of a pump impeller was simulated in this study for LMD as a well-known AM process and casting process. To study the environment impact of these two processes, an LCA was applied to establish numerical values for environmental impact in five different life cycle stages of a pump impeller. The environmental impact indicators were GWP, AP, FAETP, HTP, and ODP. The outcomes indicated that in the pre-manufacturing stage, AM process has higher environmental impact compared to casting. This was attributed to the intense electricity consumption required for the atomization process. In the manufacturing stage, LMD was superior to casting due to its low waste. Although it was favorable to casting, the low speed of the AM process increases the total energy used. Different laser power was explored and found to have little effect on the environmental effects. An increase of average power from 1 kW to 1.5 kW increased the GWP by only 2%. Ultimately, a pump impeller produced by LMD has anywhere from 10% to 65% less impact on the environment depending upon the impact category.

In conclusion the recyclability of the AM process has the greatest advantage from point of environmental protection. Although, there are weaknesses in the pre-manufacturing and manufacturing stages that cause greater strain on the environment, these weaknesses are mitigated by using electricity generated from hydro resources and renewable energy. Renewable energy sources will have lower GWP and AP compared to fossil fuels, and their use may help offset the intense energy demand of LMD.

This study is a preliminary work in this area and further research on enhancing the sustainability of AM technology is needed in future to focus on improving its sustainability in following areas:

- developing powders manufacturing technologies with lower energy consumption,
- investigating the impact of dominant parameters (SEC, built rate, powders efficiency, etc.) on the LCA of AM process,
- optimization of key parameters for the efficient outcome,
- increasing the production speed of AM process during the manufacturing. This will advance the economics of AM process as well by making it less expensive to construct the required parts.

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