Renewable and Sustainable Energy Technology
https://www.sciltp.com/journals/rset

Review

Critical Review on the Sustainability of Metal Additive Manufacturing: Environmental and Economic Perspectives

Ahmad Baroutaji [1,*], Arun Arjunan [2], John Robinson [2], Aaron Vance [2] and Abul Arafat [2]

[1] School of Engineering and Innovation, Aston University, Aston Triangle, Birmingham B4 7ET, UK
[2] Additive Manufacturing of Functional Materials Research Group, Centre for Engineering Innovation and Research, University of Wolverhampton, Telford Innovation Campus, Telford TF2 9NT, UK
* Correspondence: a.baroutaji@aston.ac.uk or a.baroutaji@gmail.com

How To Cite: Baroutaji, A.; Arjunan, A.; Robinson, J.; et al. Critical Review on the Environmental and Economic Impact of Metal Additive Manufacturing. *Renewable and Sustainable Energy Technology* **2025**. https://doi.org/10.53941/rset.2025.100006.

Received: 2 April 2025
Revised: 26 May 2025
Accepted: 14 July 2025
Published: 15 July 2025

Abstract: Manufacturing is an important pillar of socio-economic development, but it has a large carbon footprint and causes serious damage to the ecosystem. There is significant pressure on the manufacturing sector to embrace eco-friendly manufacturing technologies to reduce its environmental burden. Metal Additive Manufacturing (MAM) is a rapidly evolving field with promising prospects to balance the economic and ecological concerns. Recently, manufacturing businesses started to examine MAM as a potential route to strengthen their eco-footprint and improve sustainability performance. The shift from Conventional Manufacturing (CM) processes to MAM requires significant capital investment, staff training, and possibly changing the business model. This may lead to hesitancy among enterprises to take on such risks without guaranteeing the sustainability benefits of MAM. This paper conducts a comprehensive review and critical evaluation of the environmental and economic impacts of MAM. The paper draws guidelines on the best production contexts that enable the fulfilment of environmental goals and maintain economic viability through MAM technologies. In general, Powder Bed Fusion (PBF) techniques are considered environmentally friendly and cost-effective for small-scale production of lightweight small parts with complex shapes and relatively high resolution. In contrast, Direct Energy Deposition (DED) processes are valuable for repairing and manufacturing large-scale parts that have medium shape complexity and relatively low resolution.

Keywords: additive manufacturing; metals; environmental impact; sustainability; LCA; LCC; energy consumption; green manufacturing

1. Introduction

Since the first industrial revolution in the 18th century, manufacturing played a key role in the economic growth of many countries. On the positive side, manufacturing generates profit, wealth, and jobs, adding value to Gross Domestic Product (GDP) and employment. It helped many countries, such as China, transform their economies from low-income to high-income. On the negative side, manufacturing overburdened the environment by generating a lot of carbon dioxide (CO_2) emissions. In 2020, manufacturing was responsible for 6.22 billion tons of Greenhouse Gas (GHG) emissions and was the world's third-largest contributor to CO_2 emissions after electricity and heat production and transport [1]. Global efforts to mitigate the impact of climate change become more effective when considering strategies to reduce manufacturing-based emissions. Green manufacturing (GM), or Sustainable Manufacturing (SM), is one of the key drivers to enable long-term sustainable development and meet carbon neutrality targets. GM refers to an environmentally conscious manufacturing pattern (strategies and processes) that minimizes energy consumption and material waste, thus reducing negative environmental impacts [2]. Manufacturing is one stage in the development cycle of a product. In fact, decisions made during the design phase of a product determine, to a great degree, the materials and processes needed to make the product and may limit the options available for the manufacturing team to select environmentally friendly manufacturing operations. Thus, GM is a system-level paradigm that prioritizes environmental protection across all stages of production; therefore, it is an umbrella term for various aspects and practices such as green design, green materials, green factories, green production, and green supply chain management [3]. Embracing GM practices will not only yield environmental benefits through pollution reduction but also lead to substantial advantages in terms of operational effectiveness and economic outcomes through reducing production costs and decreasing expenses on waste treatment and disposal.

Metals are key materials in modern society because they are essential in many sectors, such as machinery, buildings, vehicles, and infrastructures. The global demand for metallic materials continues to increase at a fast pace to meet the demands of increased global populations and modern industry. This demand is expected to grow by 2–6 folds over the 21st century [4]. Conventional Manufacturing (CM) processes of metals tend to pose different environmental concerns, such as climate change and biodiversity loss, and raise concerns about how to meet the future demand for metal goods without causing further environmental damage. Therefore, it is imperative to develop a comprehensive understanding of the environmental impact of CM processes of metal and explore novel environmentally friendly fabrication ways.

Choosing a suitable manufacturing process for a certain part is a multi-criteria decision because it depends on a set of factors such as material compatibility, manufacturing constraints, production volume, lead time, cost, and quality requirements. Also, selecting the right manufacturing process is a critical step to achieve GM because the manufacturing process not only determines the energy and materials needs but also the number of subsequent treatments. Adopting manufacturing processes and routes that generate less waste and utilize less energy and material is pivotal for GM. Conventional Manufacturing (CM) processes tend to be either energy-intensive, such as casting, or material-intensive processes, such as machining. Also, the flexibility of CM processes is limited because they require bespoke tooling, such as die in casting and forging, and have constraints to produce freeform geometry without additional processes.

The advent of Industry 4.0 and its digital technologies such as big data and machine learning, cyber-physical systems, Internet of Things (IoT), autonomous robots, cybersecurity, cloud infrastructure, and Additive Manufacturing (AM) has changed the face of production processes [5]. In particular, AM has remarkable potential for solving manufacturing challenges, fostering GM practices, and creating a sustainable production system of metallic parts [6,7]. For example, products with sub-mm-scale, i.e., micro-scale geometrical features, are difficult and expensive to be produced using conventional machining while they can readily and economically be fabricated via Metal Additive Manufacturing (MAM), thanks to its layer-by-layer building approach. Recently, the field of metal AM has witnessed radical technological advancements that were translated into price reduction and quality improvement of AM products. Also, novel hybrid manufacturing strategies combining AM and CM processes were introduced to achieve advanced requirements and overcome the shortcomings of each manufacturing type. As a result, the use of AM is no longer restricted in the sphere of rapid prototyping but was extended to manufacturing functional end-use products [8]. Biomedical [9–11], automotive [12,13], aerospace [14], and energy [15–19] are some sectors that incorporated AM as a reliable production option for their parts and technologies.

AM opens a new horizon to revolutionize GM practices. However, selecting AM as a production route is a crucial strategic decision aaand may lead to an array of changes to the whole supply chain. Therefore, different aspects should be carefully evaluated before making any change. Within the context of sustainability, Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methodologies can be employed to assess environmental and economic impacts. Similarly, multi-objective approaches can be adopted to determine the optimal trade-off between the different sustainability indicators when selecting a production technology for certain products. The impact of AM, as a new technology, on sustainability continues to be debated among researchers and still no consensus has been achieved. Over the past few years, many research investigations have been undertaken to evaluate the life cycle impact of AM-manufactured products in terms of energy and material consumption, generated waste and pollution, and possible influence on human health and the environment [20]. The current paper consolidates the findings of the literature studies to clarify the environmental and economic potential of MAM. The literature review was conducted by searching through various scientific databases, including Google Scholar, Web of Science, Scopus, Science Direct, etc, using a combination of keywords, such as Metal Additive Manufacturing, Life Cycle Assessment, Sustainability, Life Cycle Costing, Cost Model, etc. The papers returned by the search were screened based on their titles and abstracts to identify those most relevant to the topic. The paper is structured as follows: Section 2 provides an overview of different MAM technologies, Section 3 reviews research studies concerned with the environmental impact and Life Cycle Assessment (LCA) of MAM technologies, Section 4 explores literature investigations on the economics of MAM, and Section 5 discusses the environmental and economic implications of MAM and identifies optimal production contexts using MAM.

2. MAM Technologies

According to ISO/ASTM 52900:2015 standard, there are seven different categories of AM processes namely Photopolymerization (VP), Material Jetting (MJ), Binder Jetting (BJ), Material Extrusion (ME), Directed Energy Deposition (DED), Sheet Lamination (SL), and Powder Bed Fusion (PBF) [21,22]. Among those methods, PBF, DED, BJ, and ME are the processes suitable for metallic feedstock. Such MAM technologies enabled the fabrication of metallic parts with controlled properties, complex shapes, and desired functionalities. PBF, DED, and BJ use metallic powder feedstock, while ME use solid metal wire feedstock.

In PBF processes, a layer of Metal Powder (MP) is deposited on a substrate in the powder bed and then either a Laser Beam (LB) or an Electron Beam (EB) is used as a heat source to selectively melt the powder feedstock in an inert atmosphere or under vacuum conditions, respectively. PBF processes can be classified, according to the type of heat source, into EB-based PBF of metals (PBF-EB/M) and LB-based PBF of metals (PBF-LB/M). PBF-LB/M is also known as Laser Powder Bed Fusion (LPBF), Selective Laser Melting (SLM), and Direct Metal Laser Sintering (DMLS) [23]. Similarly, Electron Beam Melting (EBM) was used in the literature to refer to PBF-EB/M. The vacuum and inert atmospheres used in PBF-EB/M and PBF-LB/M, respectively, are essential to reduce oxidation during the melting process and enhance the quality of the print [24,25].

In DED processes, the heat source melts the feedstock as it is being deposited on the substrate. A protecting environment in the form of a shield gas is applied to prevent oxidation of the molten pool during the DED process. The feedstock is delivered to the molten zone using co-axial or off-axis (lateral) feeding technologies. According to the type of feedstock, DED processes can be either powder or wire feeding types [26]. Powder-feeding DED processes utilize LB as thermal energy; therefore, they are called laser directed energy deposition of metals (DED-LB/M). Many other synonyms are used in the literature to refer to DED-LB/M processes including Laser Additive Manufacturing-Direct Energy Deposition (LAM-DED), Laser Direct Energy Deposition (LDED), Direct Laser Deposition (DLD), Direct Additive Laser Construction (CLAD), Laser Metal Deposition (LMD), Laser Engineered Net Shaping (LENS), Direct Metal Deposition (DMD), Direct Metal Tooling (DMT), laser deposition welding, laser cladding, etc. For wire-feeding DED processes LB, EB, Electric Arc (EA), or Plasma Arc (PA) can be used. The most popular wire-feeding DED process is Wire Arc Additive Manufacturing (WAAM) or Wire Arc Directed Energy Deposition (DED-WA). WAAM is a welding-based direct energy deposition method that uses a robotic arm, arc welding equipment, and Metal Wire (MW) feedstock to produce large metallic parts layer-by-layer [27]. The distinct application of WAAM is to fabricate large parts with a build volume exceeding 0.5 m^3, such as pedestrian footbridge [28].

Instead of heat sources used to fuse feedstock materials in PBF and DED, BJ processes use a liquid binding agent, normally organic compounds, to glue or bind metallic powder particles together. For each layer of the BJ-built part, a layer of powder is spread first in the powder bed, and then the print head dispenses the liquid binder over the powder particles to create a 2D pattern of the layer. The initial created part via BJ is called a ‘green’ part, which is a part composed of bonded powder particles. The de-binding process, which involves heating the ‘green’ part, is used to decompose and remove the binders. Following the de-binding, a pressure-less sintering process is applied to strengthen and densify the green part [29].

Table 1 summarizes the working principles, advantages, and disadvantages of different MAM methods.

Table 1. Comparison of different MAM techniques.

MAM Method	AM ISO Category	Feedstock	Heat Source	Principle	Building Requirements	Post-Processing Operations	Key Advantages and Disadvantages
PBF-LB/M	PBF	MP	LB	First, a layer of powder is deposited on a substrate in the powder bed. Then, LB melts the powder. The molten material solidifies to form a new layer of the part.	The building chamber is filled with inert gas to prevent oxidation.	• Heat treatment. • Removal of support structure.	• It can produce highly dense parts with a very high relative density of ~99% (+) [30]. • It involves a significant thermal gradient, resulting in many defects such as residual stresses and porosity as well as poor ductility (−) [30–32]. • It has a slow build rate (deposition rate) of 0.01–0.2 kg/h (−) [33]. • The printed part has internal stresses (−) [34]. • PBF-LB/M systems are expensive (−) [35–37].
PBF-EB/M	PBF	MP	EB	EB melts the powders; then, the molten material solidifies to form a new layer.	The process is done in a chamber under vacuum conditions to avoid air-electron interaction.	• Heat treatment. • Removal of support structure.	• The vacuum environment maintains the chemical composition of the material (+) [38]. • It is suitable for building highly reactive materials (materials with a high affinity for oxygen and nitrogen) such as titanium and aluminium alloys (+) [39]. • The PBF-EB/M-fabricated part has lower residual stresses and defects than that produced by PBF-LB/M (+) [39]. • Due to the vacuum environment, the PBF-EB/M-fabricated part has a higher relative density and lower defects than the PBF-LB/M-fabricated one (+) [39]. • Its deposition rate (0.041–0.13 kg/h) is comparable to PBF-LB/M (−) [40]. • It is faster than PBF-LB/M due to wider spot size and higher power of EB compared to LB (+) [41].
DED-LB/M	DED	MP	LB	It uses the concept of cladding and welding processes where the part is created line-by-line through the simultaneous deposition of material and energy, i.e., LB melts the powder materials as they are deposited onto the substrate.	Inert gas is used in the building chamber.	• Finishing operations to enhance surface quality. • Heat treatment, such as HIP, to minimize residual stresses.	• It has lower dimensional accuracy/resolution and higher surface roughness and deposition rate than PBF (−) [26]. • The minimum feature size of the DED-LB/M fabricated part is greater than that obtained by PBF methods (−) [26]. • It can be used for large parts (+) [26]. • It can be used for even and uneven substrates (+) [26]. • The building rate is in the range of 0.5–6 kg/h, which is faster than PBF processes (+) [42]. • It can be used for repair (+) [26].

Table 1. *Cont.*

MAM Method	AM ISO Category	Feedstock	Heat Source	Principle	Building Requirements	Post-Processing Operations	Key Advantages and Disadvantages
WAAM	DED	MW	EA	The wire feedstock is simultaneously fed and melted, using electric arc, onto the surface of the substrate.	Inert gas.	• Heat treatment processes such as annealing and Hot Isostatic Pressing (HIP).	• It has low capital investment and it is cheaper than DED-LB/M and PBF processes (+) [30,43]. • It has a high deposition rate in the range of 1–8 kg/h (+) [44]. • It is suitable for large-sized structures with medium geometric complexity (−) [44]. • Its dimensional accuracy is inferior to DED-LB/M (−) [26]. • It has less health and safety concerns than PBF and DED-LB/M as they don't use powder feedstock (+) [45]. • It offers less energy consumption than DED-LB/M and PBF due to the use of EA as an efficient fuse source [45].
BJ	BJ	MP	NA	First, a layer of powder feedstock is deposited on the building plate. Then, a liquid binding agent is applied to join powder materials in selective areas of each layer.	None	• De-binding. • Sintering. • Infiltration (optional) to increase the density of the part.	• It has a large build volume (+) [29]. • It can print a wide range of materials, including those with high optical reflectivity, high thermal conductivity, and low thermal stability [46]. • It has a relatively high build rate (200 cm3/min) compared to MJ processes (+) [29]. • BJ process requires no protective environment, such as vacuum used in PBF-EB/M or inert gas used in PBF-LB/M or DED-LB/M (+) [46]. • It doesn't require support structures (+) [46]. • The MJ-fabricated part has a relatively low density (−) [46]. • Sintering causes significant dimensional change where the shrinkage during sintering may reach 15%–20% (−) [29].

3. Environmental Performance of MAM

3.1. Environmental Assessment Tools

The environmental advantage of MAM can be assessed by its ability to reduce material utilisation, decrease energy consumption, and process an eco-friendly material. LCA is an effective tool for evaluating the impact of MAM on global environment [33,47]. Unlike conventional assessment methods that only consider one stage of the product development cycle, LCA is a comprehensive method that examines energy and material flow and assesses the environmental impact during the different stages, or gates, of the product life cycle from materials extraction until product disposal, as shown in Figure 1. Depending on its scope, LCA can be either comprehensive or partial. The comprehensive LCA, or cradle-to-grave LCA, considers all product life stages. Conversely, partial LCA considers only a limited number of stages within the product life span and can be classified into cradle-to-gate, gate-to-gate, or gate-to-grave.

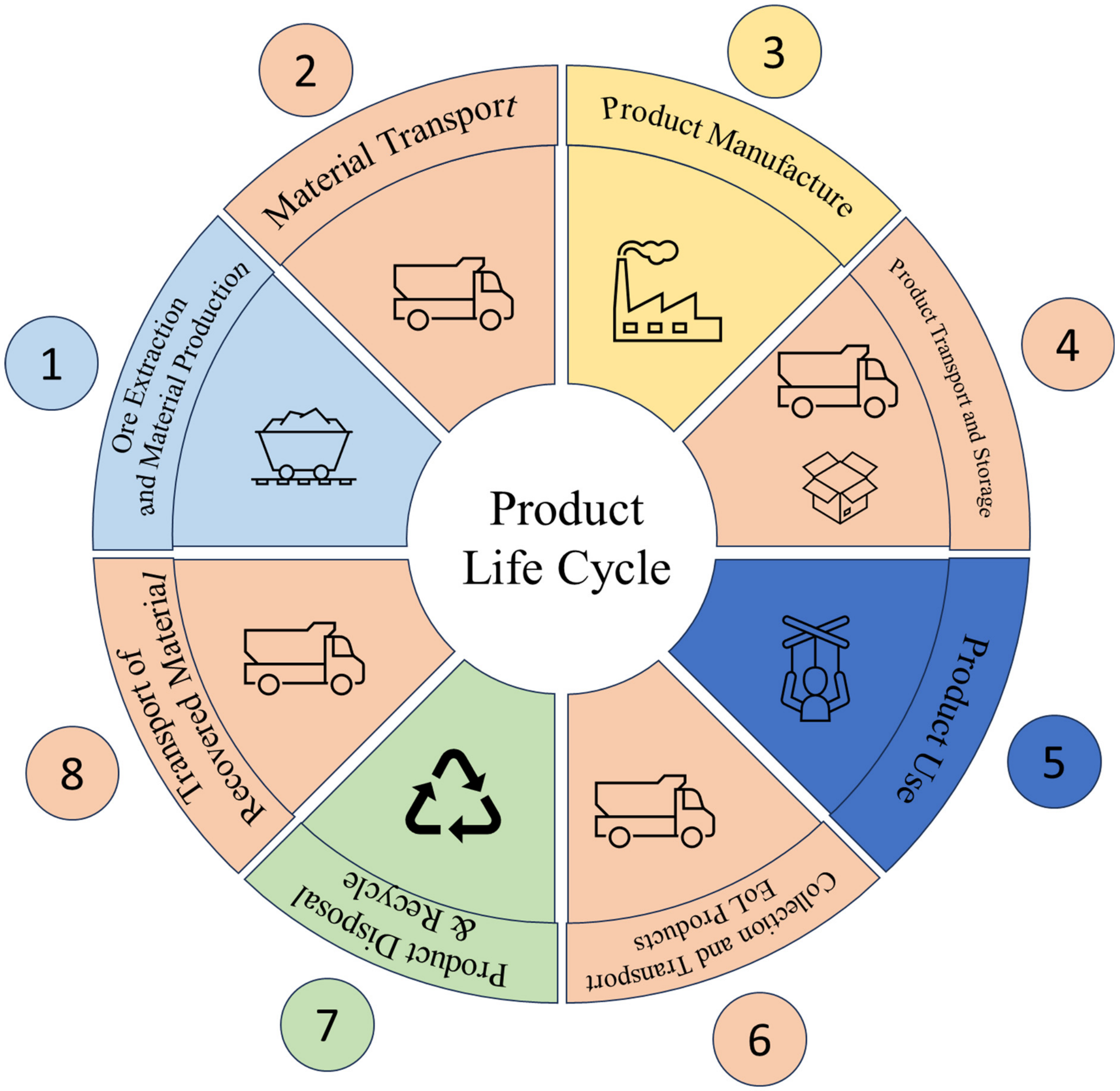


Figure 1. Product life cycle from material extraction till disposal. Transport of feedstock and manufactured and used product and recovered material are intermediated stages. Material and energy are the input for each stage while emissions (in solid, liquid, and gaseous forms) and waste hear are outputs.

ISO14040 standard prescribes the LCA procedure and framework [48]. According to this standard, the LCA study consists of four main steps, as shown in Figure 2, including first, defining goals and scope; second, compiling an inventory of inputs and outputs for materials, energy, and emissions; third, assessing the impact associated with the inputs and outputs; and fourth, interpreting the results of inventory analysis and impact evaluation with respect the objective of the study. The LCA study is typically conducted for a particular functional unit (product) to provide a reference to which inputs and outputs are mapped.

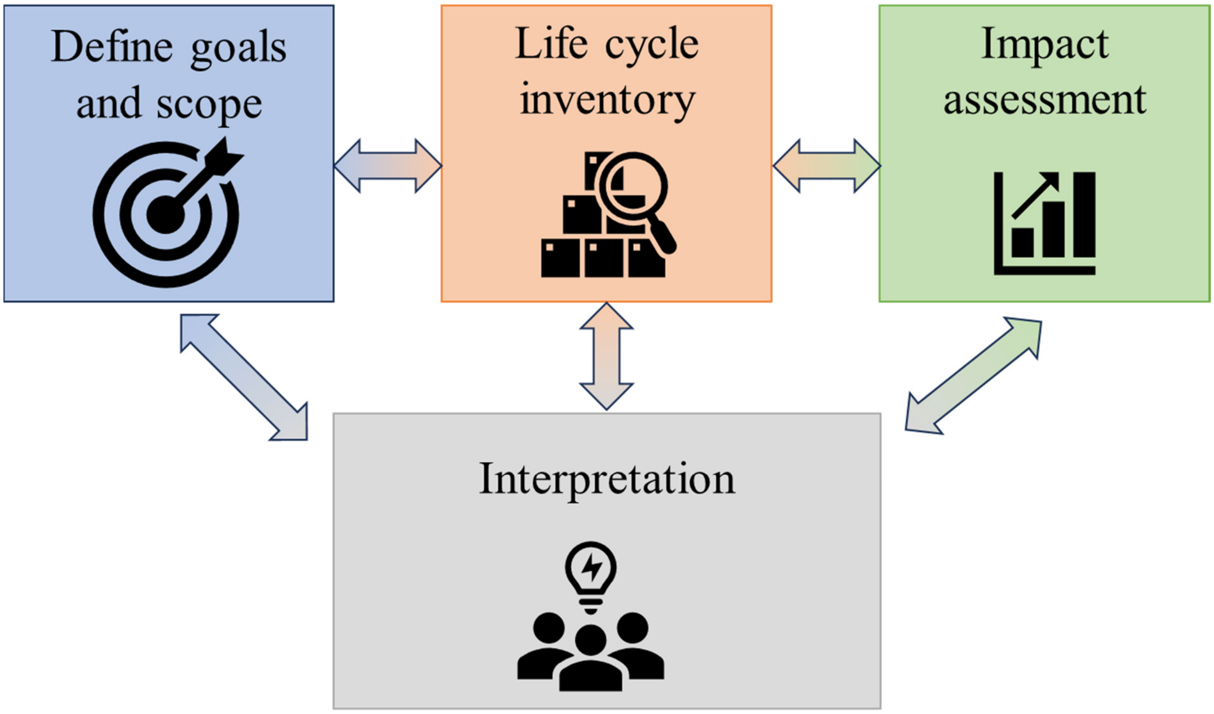


Figure 2. The ISO14040 standard LCA framework.

In the subsequent sections, literature studies on LCA research of different MAM technologies were reviewed to assess the environmental impact of MAM. Also, the studies that merely focused on comparing energy or material consumption of the AM and CM processes were surveyed. Table 2 summarizes previous research investigations on the LCA of MAM.

Table 2. Summary of MAM LCA investigations.

MAM Method	Material	LCA Scope	Functional Unit	Main Findings	Ref
PBF-LB/M	Aluminium alloy (AlSi10Mg)	Cradle-to-grave	A component with an axisymmetric geometry.	• CM techniques (machining and forming) are more sustainable than PBF-LB/M for fabricating parts with simple geometries. • PBF-LB/M is more environmentally friendly than machining or forming processes for fabricating aircraft parts with complex shapes (have low solid-to-cavity ratios).	[49]
PBF-LB/M	Stainless steel (316L)	Cradle-to-gate	Hydraulic valve body.	• The PBF-LB/M process can reduce the environmental impact of producing the standard valve design by 37.42% compared to the CM method. • The powder preparation stage and electrical demands of the process are the main causes of the negative environmental impact of the PBF-LB/M process.	[50]
PBF-LB/M	• Aluminium alloy (AlSi10Mg). • Stainless steel (316L)	Gate-to-gate	• A sprocket adapter made of aluminium alloy (AlSi10Mg). • A tie rod made of stainless steel (316L).	• PBF-LB/M-fabricated parts have a lower environmental impact than machined parts.	[51]
PBF-LB/M	Inconel 718	Gate-to-gate	A jet engine turbine blade	• PBF-LB/M produces 4% less CO_2 emissions than CM (investment casting combined with precision machining).	[52]
PBF-LB/M	Stainless steel (316L)	Cradle-to-grave	• An air ejector • A centric orifice plate.	• PBF-LB/M is more environmentally demanding than conventional subtractive machining methods due to the high electrical demands of the PBF-LB/M process.	[53]
PBF-LB/M	Stainless steel (316L)	Cradle-to-grave	A flat washer.	• CM using CO_2 laser cutting is more environmentally friendly and economical than PBF-LB/M.	[54]
• PBF-LB/M • PBF-EB/M	Stainless steel (316L)	Cradle-to-gate	A part with an axisymmetric geometry and holes.	• The PBF-EB/M process is more eco-friendly than PBF-LB/M and machining processes.	[55]
PBF-LB/M	Aluminium alloy (AlSi10Mg)	Cradle-to-grave	A small turbine.	• The electricity consumption of the PBF-LB/M process has the highest share of its environmental impact.	[56]
PBF-LB/M	Aluminium alloy (AlSi10Mg)	Cradle-to-gate	A rocker arm.	• PBF-LB/M process has less environmental damage than machining for fabricating a part with a topology-optimized geometry. • Machining is more eco-friendly than PBF-LB/M for producing the standard geometry of the part.	[57]

Table 2. *Cont.*

MAM Method	Material	LCA Scope	Functional Unit	Main Findings	Ref
PBF-LB/M	Various materials (see function unit column).	Cradle-to-grave	An automotive engine with different components made of different materials, such as cast iron, stainless steel, low-alloy steel, and aluminium alloy.	• PBF-LB/M has the potential to improve environmental performance if future technological developments enable the printing of low-alloy steel engine parts.	[58]
PBF-LB/M	Titanium alloy (Ti6Al4V)	Cradle-to-grave	An aeroplane doorstop.	• PBF-LB/M has less environmental burden but is more expensive than conventional machining.	[59]
• PBF-LB/M • PBF-EB/M	Various materials (see function unit column).	Cradle-to-gate	Different representative aircraft components: • Fork fitting made of titanium alloy. • Bracket made of titanium alloy. • Seat buckle made of aluminium alloy. • Bionic bracket made of titanium alloy. • Engine cover door hinge made of titanium alloy.	• Adopting AM for the aircraft industry could result in substantial energy savings and reductions in GHG emissions.	[60]
• PBF-LB/M • PBF-EB/M	• Titanium alloy (Ti6Al4V). • Stainless steel	Cradle-to-gate Cradle-to-grave	A single produced part.	• The hybrid manufacturing approach combining AM methods with finish machining is more eco-friendly than conventional subtractive machining. • The use phase influences LCA results of components, which are parts of a transportation system, such as cars and aircrafts.	[61]
PBF-LB/M	Carburizing steel (16MnCr5)	Cradle-to-gate	An industrial gear wheel.	• The machining process is more energy-efficient than PBF-LB/M for standard gears. • PBF-LB/M is more energy-efficient than machining for fabricating gears with lightweight designs at a small production volume.	[36]
• PBF-LB/M • Additive Friction Stir Deposition (AFSD)	Titanium alloy (Ti6Al4V)	Cradle-to-gate	1 kg of blocks.	• The AFSD process has better sustainability performance than the PBF-LB/M process. • The lower sustainability score of PBF-LB/M is due to the high energy demands of the powder preparation process and the need for argon protective gas during the process.	[62]
PBF-LB/M	Nickel-based super alloy	Cradle-to-gate	Repairing a gas turbine burner.	• The PBF-LB/M-based repair reduces energy consumption, carbon footprints, and material footprints compared to conventional repair using machining and welding processes.	[63]
PBF-LB/M	Stainless steel	Cradle-to-gate	Metallic components of an electric ducted fan.	• PBF-LB/M in a distributed manufacturing scenario has a lower environmental impact than conventional machining in a centralized manufacturing scenario.	[64]

Table 2. *Cont.*

MAM Method	Material	LCA Scope	Functional Unit	Main Findings	Ref
PBF-EB/M	Titanium alloy (Ti6Al4V)	Gate-to-grave	Manufacturing one turbine.	• PBF-EB/M is more eco-friendly than CNC milling.	[65]
PBF-EB/M	Titanium alloy (Ti6Al4V)	Cradle-to-grave	A femoral component of a knee implant.	• PBF-EB/M has better ecological performance than milling, requiring less materials, consuming less energy, and releasing less carbon emissions.	[66]
PBF-EB/M	Titanium alloy (Ti6Al4V)	Cradle-to-grave	A component with an axisymmetric geometry.	• PBF-EB/M is a more sustainable manufacturing strategy than machining for parts with complex geometry. • Machining has better sustainability performance than BEM for parts with simple designs.	[67]
DED-LB/M	Titanium alloy (Ti6Al4V)	Cradle-to-gate	A mechanical part with complex geometrical patterns.	• The DED-LB/M process caused less damage to the environment, natural resources and human health compared to machining. • The main driver of DED-LB/M environmental impact was the powder preparation.	[68]
DED-LB/M	Titanium alloy	Cradle-to-gate	Turbomachinery impeller.	• Compared to machining, additive remanufacturing, and hybrid additive-subtractive, the pure additive manufacturing approach by the DED-LB/M process was the least eco-friendly option for impeller production due to its high electricity demands.	[69]
DED-LB/M	Hot work tool steel (H13)	Cradle-to-gate	One functional mould of a glass bottle.	• The DED-LB/M-based repair was more cost-effective and environmentally friendly than the conventional repair.	[70]
• WAAM • PBF-LB/M	High strength low alloy steel (ER70)	Cradle-to-gate	A marine propeller	• The material efficiency of PBF-LB/M was higher than that of WAAM and pure milling. • The WAAM process had the lowest environmental impact, while the PBF-LB/M had the highest impact.	[37]
• WAMM • PBF-LB/M	High strength low alloy steel (ER70)	Cradle-to-gate	A flat wall.	• The CNC milling was the most ecological manufacturing option for the considered component. On the other hand, • PBF-LB/M had the most environmental impact due to the high energy demand and shielding gas requirements.	[71]

Table 2. *Cont.*

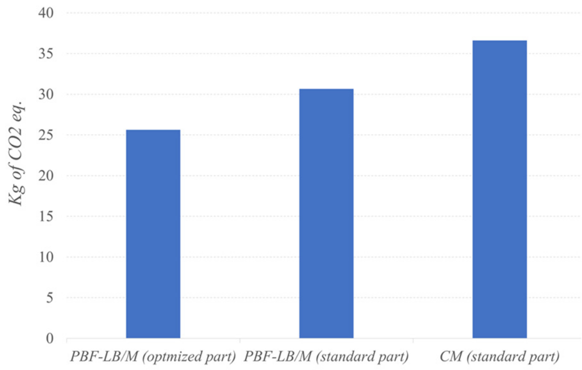
MAM Method	Material	LCA Scope	Functional Unit	Main Findings	Ref
WAAM	High strength low alloy steel (ER70)	Cradle-to-gate	Three different parts • A gear • A Cylinder • S-shaped geometry	• WAAM demonstrated higher material savings and reduced environmental impact compared to the milling operation. • The environmental impact associated with the Wire Arc Additive Manufacturing (WAAM) process primarily stems from the production of primary material and the consumption of shielding gas.	[72]
WAAM	Stainless steel (316L)	Cradle-to-gate	An engineering part.	• Preparation of feedstock material, energy consumption, and the use of shielding gas were the main reasons for the WAAM's environmental impact. • WAAM exhibited a lower impact on human health, ecosystems, and resources than the machining process.	[73]
WAAM	Structural mild steel (ER70S-6)	Cradle-to-gate	A component containing cavities.	• The integrated manufacturing approach combining WAAM with finishing milling operation was more environmentally friendly than the traditional machining approach.	[27]
WAAM	Structural steel (EN S235JR)	Cradle-to-gate	A blade.	• The integrated WAAM-machining approach enabled materials and energy savings compared to the pure machining approach.	[74]
WAAM	• Aluminium alloy (AA2319) • Structural mild steel (ER70S-6) • Titanium alloy (Ti6Al4V)	Cradle-to-gate	• Aerospace frame made of AA2319 • Cantilever beam made of ER70S-6 • Titanium aerospace bracket made of Ti6Al4V	• The WAAM-based integrated additive/subtractive production approach was found to yield a remarkable reduction in CO_2 emissions and energy consumption in comparison to machining.	[75]
WAAM	Hot work tool steel (H13)	Cradle-to-gate	Mould inserts used in the casting process.	• The AM-based repair approach was more environmentally friendly than the conventional substitution-based approach.	[76]
BJ	Stainless steel (316L)	Cradle-to-gate	Plates for microscale chemical reactors	• BJ was more eco-friendly than MIM for low production volumes, and vice versa.	[66]

3.2. PBF

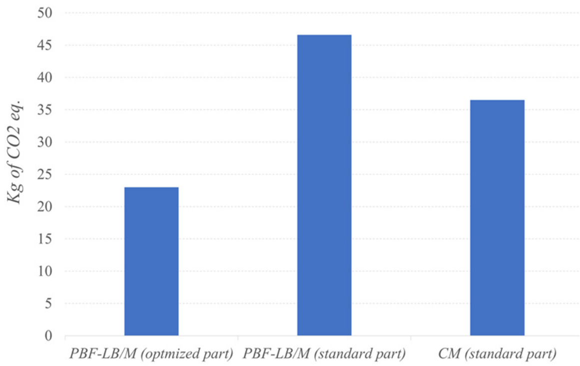
3.2.1. PBF-LB/M

The PBF-LB/M process was the most investigated MAM process in terms of its environmental impact. Many studies reported that PBF-LB/M has a higher environmental impact than CM or other MAM processes due to its high energy demands. Kellens et al. [77] evaluated the environmental impact of PBF-LB/M-fabricated stainless steel (316L) parts. They revealed that the environmental burden of the PBF-LB/M process is greater than that generated during the material production phase. This was mainly due to the high electrical energy consumption of the PBF-LB/M process. The melting phase was the most energy-demanding phase, accounting for 80% of total energy consumption. Ingarao et al. [49] evaluated the environmental impact of PBF-LB/M, machining, and forming manufacturing techniques for fabricating aluminium (AlSi10Mg) components via applying cradle-to-grave LCA. They reported that CM approaches were more environmentally friendly than PBF-LB/M for simple parts that do not have AM-oriented geometries. The power required for the laser to process the aluminium was the most impactful factor on the environmental performance of the PBF-LB/M process. The study showed that PBF-LB/M can only be more sustainable than CM approaches if it enables shape complexity with significant weight reduction, i.e., parts with low solid-to-cavity ratio, and the manufactured part is used on an aircraft. Similar findings were reported by Výtisk et al. [53], who conducted cradle-to-grave LCA to compare PBF-LB/M and CM for fabricating an air ejector and a centric orifice plate. They found that PBF-LB/M was more environmentally demanding in most impact categories and is also a more energy-intensive process, requiring 30% more Primary Energy Demand (PED) than CM. The high PED of the PBF-LB/M process may drop by recycling the metal wastes from support structures and the powder sieving process. The high energy consumption of the PBF-LB/M process was due to the laser cooling phase, which consumes four times more energy than the printing phase. The negative environmental impact of the PBF-LB/M process caused by its high energy consumption was also noted by Guarino et al. [54], who performed LCA to compare PBF-LB/M and CO_2 Laser Cutting (LC) processes for manufacturing flat washers. They found that the damaging impact of PBF-LB/M was four times greater than LC. Faludi et al. [56] used LCA to determine the phase that has the most environmental impact during the PBF-LB/M process of aluminium parts. They found that the electricity consumption of the process accounts for around four-fifths of embodied energy, thus dominating the environmental impact. They attributed the high energy consumption of the process to the auxiliary equipment and processes, such as the chiller of the PBF-LB/M system and Electron Discharge Machining (EDM) used for part removal. Ahmed et al. [62] conducted a comprehensive sustainability comparison of two MAM methods, including Additive Friction Stir Deposition (AFSD) and PBF-LB/M. The comparison was conducted utilising the LCA framework for producing 1 kg of titanium (Ti6Al4V) blocks. The authors found that AFSD had a superior sustainability performance than PBF-LB/M and attributed this to the high energy consumption associated with preparing powder material and supplying argon protective gas required for the PBF-LB/M process. The sensitivity analysis revealed that build volume, production speed, and material cost are the main factors influencing the sustainability score of AM processes.

Despite the high energy demand, PBF-LB/M can still be more sustainable than CM for producing parts with complex geometry or lightweight parts with topology-optimized geometries because CM of such parts is challenging and often requires multiple steps and technologies [49]. Figure 3 shows some examples of attaining better environmental performance for PBF-LB/M when utilized for parts with optimized geometries. Torres-Carrillo et al. [52] adopted gate-to-gate LCA to conduct an environmental impact analysis of PBF-LB/M for manufacturing a jet engine turbine blade. It was found that PBF-LB/M can yield up to a 4% reduction in the total CO_2 emissions compared to the CM route using Investment Casting (IC) and Precision Machining Manufacturing (PMM) processes. 7.027 and 7.325 tons of CO_2 emissions were estimated to be produced during the whole life cycle of 600 blades manufactured by PBF-LB/M and CM, respectively. Peng et al. [50] and Wang et al. [78] conducted a cradle-to-gate LCA analysis to estimate the environmental impacts of PBF-LB/M-fabricated hydraulic valve bodies with standard and optimized designs. The PBF-LB/M approach was compared with CM using lost-wax casting and machining processes. The PBF-LB/M process yielded a 37.42% reduction in environmental impacts compared to CM when used to produce the standard design of the part. Interestingly, the environmental impact of PBF-LB/M when producing the optimized design was only 10–23% less than CM, indicating that PBF-LB/M may have a more profound environmental impact when used to fabricate an optimized part with lightweight potential. The powder preparation stage and the high electricity consumption were the main reasons for the high environmental damage of PBF-LB/M. Swetha et al. [51] utilized gate-to-gate LCA to compare the environmental impact of Conventionally Manufactured (CMed) and PBF-LB/M-fabricated (PBF-LB/Med) parts, including sprocket adapters and tie rods. The findings showed that topology-optimized PBF-LB/M-fabricated parts had less impact on the ecosystem, human health, and resources compared to PBF-LB/Med and CMed components without topology optimization. The good environmental performance of optimized PBF-LB/Med parts was because they required less building time and consumed less energy during the manufacturing process. Ramadugu et al. [57] used cradle-to-gate LCA to compare the environmental impact of PBF-LB/Med and machined automotive rocker arms. Topology optimization and Design for Additive Manufacturing (DfAM) approaches were applied to redesign the part with less weight for PBF-LB/M. The PBF-LB/Med part with topology-optimized geometry exhibited 21.31% less environmental damage than the machined part. On the other side, the machined part has 14.53% less environmental impact than the PBF-LB/Med part without topology optimization. The primary cause of the environmental footprint of the PBF-LB/Med part is the high energy consumption during the printing process. Kamps et al. [36] employed cradle-to-gate LCA framework to identify the most energy-efficient production scenario for industrial steel gear wheel. Three manufacturing methods including machining, hobbing, and PBF-LB/M; and three design variants of the part, including one standard and two lightweight designs, are evaluated for low- and high-volume production scenarios. The milling process was more energy-efficient than PBF-LB/M and hopping for standard gears. PBF-LB/M was competitive with other manufacturing processes in terms of energy efficiency for fabricating lightweight design gear at a small production scale.



(**a**)



(**b**)

Figure 3. Estimated cradle-to-gate CO_2 kg equivalent for manufacturing (**a**) stainless steel hydraulic valve body (**b**) aluminium rocker arm (produced based on data reported in [50,57]).

PBF-LB/M process showed environmental benefits for producing lightweight parts for automotive and aeronautical applications. Bockin and Tillman [58] used LCA to estimate the potential environmental effects of using PBF-LB/M for fabricating metallic engine parts for a light distribution truck. The authors stated that PBF-LB/M has the potential to improve the life cycle environmental performance by fabricating advanced lightweight engine parts with improved functionalities. Such potential can be achieved if future technological developments enable PBF-LB/M to process low-impact materials, such as low-alloy steel, rather than highly impacting materials, such as stainless steel and nickel alloys. Mami et al. [59] conducted LCA to explore the eco-efficiency of PBF-LB/M as a manufacturing approach for titanium aeroplane doorstops. PBF-LB/M was more eco-efficient and had less environmental burden than machining. Huang et al. [60] conducted a cradle-to-gate study to estimate the net changes in GHG emissions and life-cycle primary energy consumption associated with adopting PBF-EB/M and PBF-LB/M for the production of different lightweight metallic aircraft components. The results indicated that MAM could lead to an annual energy saving of 70–173 million GJ and a reduction in GHG emissions of 5.4–13.3 million tons of CO_2 equivalent in 2050. The study also projected that MAM could save thousands of tons of aluminium, titanium, and nickel alloys by 2050. This work demonstrated the potential of MAM in enabling the aircraft industry to meet long-term sustainability goals.

PBF-LB/M process may yield some environmental advantages if used in the hybrid additive-subtractive manufacturing approach. Priarone and Ingarao [61] compared the required PED and released CO_2 emissions associated with manufacturing titanium alloy (Ti6Al4V) and stainless steel parts using purely machining and hybrid additive-subtractive production routes. PBF-LB/M and PBF-EB/M processes were evaluated for the hybrid production scenario. The hybrid approach with the ability to fabricate lightweight and highly surface-finished parts is the most eco-friendly approach for parts of transportation systems (automotive and aerospace parts). The study showed that the impact of the use phase on LCA results is significant if the part belongs to a transportation system. Ahmad and Enemuoh [55] conducted cradle-to-gate LCA assessment and developed analytical models to estimate the energy consumption of hybrid additive-subtractive, combining PBF-LB/M with milling for producing stainless steel (316L) parts. Solid-envelope ratio was used to define the geometrical shape of the parts manufactured in this work. The hybrid approach was compared with PBF-EB/M and conventional milling processes. It was found that the part production stage of the hybrid process is the most energy-demanding phase, consuming an average of 84% more energy than PBF-EB/M and conventional milling processes. On the other side, the primary material production stage was the highest energy consumption phase in the milling process, requiring an average of 70% more energy than the PBF-EB/M and hybrid processes. Regardless of the solid-envelope ratio, PBF-EB/M was the most eco-friendly process with the lowest total energy consumption.

PBF-LB/M can also be environmentally beneficial for repair applications. Walachowicz et al. [63] utilized a cradle-to-gate LCA framework to compare the environmental impact of PBF-LB/M-based with conventional repair methods of a gas turbine burner. The considered burner consisted of a main body made of stainless steel and an upper section made of nickel-based superalloy. The conventional repair process involved replacing the damaged parts of the burner with new prefabricated parts having the same geometry and materials. Different welding technologies and finishing processes were used in the conventional repair approach. Conventional repair might sometimes involve removing/replacing undamaged parts. The PBF-LB/M-based repair involved removing the damaged part only and then building a new one using a customized PBF-LB/M system. The PBF-LB/M-based repair provided many sustainability and environmental benefits as it yielded significant reductions in PED, carbon footprint, and material footprint compared to conventional repair using machining and welding processes.

Decentralized manufacturing is another context where PBF-LB/M can yield environmental benefits. Tran et al. [64] performed cradle-to-gate LCA analysis to compare the energy consumption of PBF-LB/M and CM for producing stainless steel parts for an electric ducted fan in a decentralized manufacturing setting. The study found that the transportation cost of the centralized manufacturing scenario via CM had a greater impact on the overall energy consumption, ranging between 3 and 4.4 times that of the decentralized manufacturing scenario using AM. This research proved the distinct environmental advantage of AM over CM in a distributed manufacturing setting.

3.2.2. PBF-EB/M

Paris et al. [65] compared the environmental impacts of manufacturing a titanium alloy (Ti6AlV) aeronautic turbine using PBF-EB/M and CNC milling approaches. The study utilized manufacture-to-grave LCA that considered three life cycle phases: production, use, and end-of-life (EoL). The results showed that PBF-EB/M was a more environmentally friendly manufacturing option than CNC milling as it generated lower environmental impacts. However, the study noted that the milling process could reach the same environmental impact as PBF-EB/M if the starting part had a close geometry to the final part. A similar observation was also reported by Lyons et al. [66] who evaluated the environmental impact associated with manufacturing a femoral component of a titanium (Ti6Al4V) knee implant. The authors compared PBF-EB/M and milling manufacturing methods using cradle-to-grave LCA, focusing on CO_2 emissions and PED. The study found that PBF-EB/M had better sustainability performance than milling, consuming 45.5% lower PED and releasing 31.8% less CO_2. The good ecological performance of PBF-EB/M was attributed to its high material efficiency, which was 65% compared to 15% in the milling process. The poor material efficiency of the milling process was due to the complex geometry of the part. PBF-EB/M produced 3.9 times less CO_2 emissions per part compared to the milling process. The preparation of material powder in the PBF-EB/M process was the most polluting stage, accounting for 76.8% of the total CO_2 emissions. Priarone et al. [67] conducted a cradle-to-grave LCA to compare the PBF-EB/M and machining processes, in terms of energy efficiency and CO_2 emissions, for fabricating titanium (Ti6AL4V) parts. They reported that for parts with complex geometry having a small solid-to-cavity ratio, PBF-EB/M was a more sustainable manufacturing strategy. This was due to PBF-EB/M utilizing less material, consuming less overall energy, and releasing less CO_2 emissions than machining. Conversely, for simple parts with a high solid-to-cavity ratio, the high energy demand of PBF-EB/M surpassed the material savings, resulting in lower sustainable performance and higher CO_2 emissions. Therefore, sustainable performance is not only dependent on the used manufacturing process but also on the geometrical features of the part. Baumers et al. [79] compared the energy consumption of PBF-EB/M and CNC machining for fabricating titanium parts with different levels of shape complexity. They used a convexity-based metric to quantify the shape complexity of the parts. They found that energy consumption of PBF-EB/M was not driven by the shape complexity of the part, indicating a weak connection between the two.

Le et al. [80] conducted an environmental assessment for hybrid additive-subtractive manufacturing. They used PBF-EB/M with machining to transfer an existing part into a new part. They revealed that the hybrid PBF-EB/M-machining route was more environmentally friendly than the CM strategy involving casting and machining if more than 60% of the existing part material was reused for the new part. The environmental burden of the hybrid manufacturing strategy was mainly due to the electricity- and resources-intensive nature of the powder production and the PBF-EB/M process.

3.3. DED

3.3.1. DED-LB/M

Serres et al. [68] compared the environmental impact of machining with the DED-LB/M process (termed CLAD) for titanium alloy (Ti6Al4V) parts using cradle-to-gate LCA. The study found that the DED-LB/M process had 70% less environmental impact than machining and resulted in reduced damage to natural resources and human health. The largest environmental impact of DED-LB/M was during the powder production phase. Peng et al. [69] conducted a cradle-to-gate LCA assessment to compare the environmental impact of different manufacturing methods for impeller production, including machining (milling), hybrid additive-subtractive approach, AM using DED-LB/M, and additive remanufacturing. The research concluded that additive remanufacturing was the most environmentally friendly approach, while pure AM was the least favourable due to its high environmental burden caused by its high electricity requirements. Gouveia et al. [70] compared the economic and environmental performances of DED-LB/M and casting in the context of repairing a damaged glass bottle mould. The authors assessed two repairing scenarios: using casting to produce a new mould to replace the damaged one or using the DED-LB/M process to repair the damaged mould. The DED-LB/M-based repair involved three steps, including machining of the damaged area, deposition of material via DED-LB/M, and then machining again to obtain the final geometry. The DED-LB/M-based repair was more cost-effective and environmentally friendly than the conventional repair. The DED-LB/M-based repair resulted in 2.62 kg CO_2 equivalent, while the conventional repair released 10.95 kg CO_2 equivalent.

3.3.2. WAAM

In general, WAAM has lower energy demands than laser-based MAM processes because it uses an electric arc as a heat source. This feature enabled WAAM to exhibit better environmental performance than laser-based MAM processes, such as PBF-LB/M, as shown in Figure 4. Kokare et al. [37] conducted a comparative analysis of the environmental impact of PBF-LB/M, WAAM, and CNC milling in the production of marine propellers made of ER70 steel. The cradle-to-gate LCA revealed that PBF-LB/M exhibited the highest material efficiency of at 58%, consuming 1.3 times and 5.8 times less raw material (powder) than WAAM and pure CNC milling, respectively. On the other hand, WAAM was found to yield 2.5 times and 3.4 times less environmental impact compared to CNC and PBF-LB/M. The work highlighted the high energy requirements of the PBF-LB/M as the main driver of the high environmental impact. In a similar work, Kokare et al. [71] used cradle-to-gate LCA to compare the environmental impact of manufacturing a single wall using WAAM, CNC milling, and PBF-LB/M. They found that the CNC milling process was the most ecological manufacturing option for the considered component. On the other hand, PBF-LB/M was the least favourable option due to its high environmental impact caused by the use of Argon shielding gas and the high energy consumption during the process.

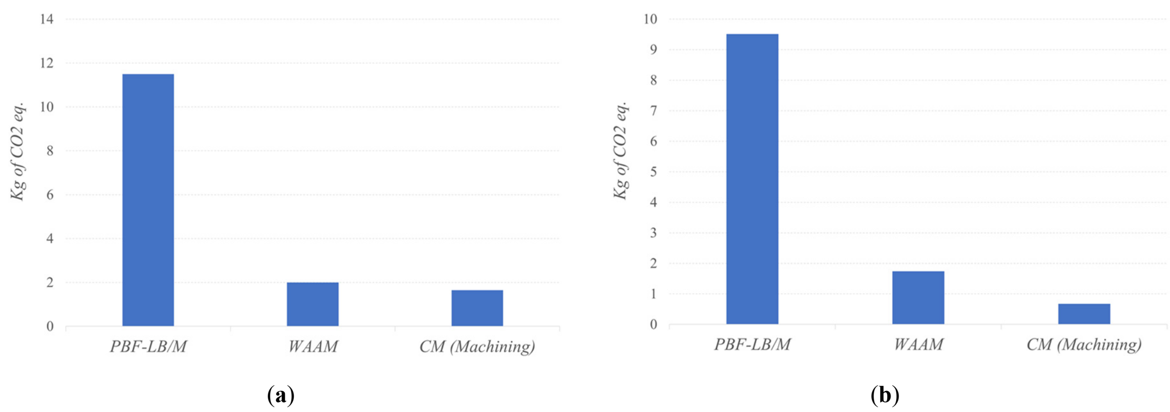


Figure 4. Estimated cradle-to-gate CO_2 kg equivalent for manufacturing (**a**) high-strength low-alloy steel part with modesty complicated shape (**b**) ER70 Steel wall (produced based on data reported in [71,81]).

Reis et al. [72] used cradle-to-gate LCA comparative analysis to quantify the environmental impact of WAAM and CNC milling operation for fabricating three steel parts, including a gear, cylinder, and S-shaped geometries. The study found that using AM for metal products resulted in 40%-70% material savings and a 12%-47% reduction in the environmental impact compared to CNC milling. The production of primary material, i.e., the steel billet, and the consumption of shielding gas were the main contributors to the environmental impact of WAAM. On the other side, the hot rolling process, used in both manufacturing routes, had the lowest environmental impact. Dial et al. [73] performed a cradle-to-gate LCA analysis to compare the environmental performance of WAAM and traditional machining processes. The evaluation focused on a part made of stainless steel (316L). The analysis revealed that the primary contributors to the environmental impact of the WAAM process were the preparation of feedstock material, energy consumption during the process, and the use of argon as a shielding gas. A comparison between WAAM and the machining process showed that WAAM had distinctive environmental advantages, exhibiting a lower impact on human health, ecosystems, and resources. The study highlighted that the remarkable sustainability behaviour of the WAAM process stemmed from its high material utilisation and low material waste. Catalano et al. [82] studied the influence of WAAM process parameters on cradle-to-gate economic and environmental performance of titanium alloy (Ti6Al4V) parts. The research revealed a negligible effect of the deposition rate on the environmental performance of the parts, as most of the carbon footprint and the energy demand were associated with the pre-manufacturing phase, specifically the material production stage. However, the deposition rate did affect the production time and manufacturing costs. Increasing the deposition rate can reduce the production time by 25%. The study also highlighted that the environmental impact of CM was higher than that of the WAAM process in parts with complex geometries featuring low solid-to-cavity ratios or high Buy-To-Fly (BTF) ratios. Shah et al. [83] conducted a cradle-to-gate LCA to compare the environmental impact of using WAAM and hot-rolling techniques for manufacturing steel beams. They considered topology-optimized truss structures with tubular elements for the WAAM process and simple I-section beams for the hot rolling process. The study found that WAAM-manufactured stainless steel and carbon steel beams have 24% and 7% less environmental impact than the corresponding hot-rolled I-beams. The research pointed out that the shielding gas used in the WAAM process had the greatest environmental impact, even surpassing the impact of electricity consumed during the process. The researchers suggested that the environmental performance of WAAM can be improved further by increasing the material deposition rate, which would reduce the consumption of both shielding gas and electricity. Priarone et al. [75] used cradle-to-gate LCA and a multi-criteria decision-analysis method to compare the environmental impacts of products manufactured by WAAM and machining processes. The authors looked at medium-to-large metallic parts, including an aluminium (AA2319) aerospace frame, steel (ER70s-6) cantilever beam, and titanium (Ti6Al4V) aerospace bracket. The study focused on cumulative CO_2 emissions and Cumulative Energy Demand (CED) as environmental performance metrics. The results showed that using WAAM can significantly reduce CO_2 emissions and energy consumption.

The results of cradle-to-gate LCA conducted by Priarone et al. [27] showed that the integrated manufacturing approach, combining WAAM with finishing milling operation, had lower energy requirements and carbon footprint than the traditional machining approach for manufacturing mild steel parts with a relatively low solid-to-cavity ratio. The study also demonstrated that the environmental metrics of the two approaches may converge as the solid-to-cavity ratio increases. Therefore, the solid-to-cavity ratio can be considered a useful indicator for making informed decisions in manufacturing planning. In a similar work, Campatelli et al. [74] applied a cradle-to-gate LCA to compare PED and material consumption of integrated WAAM-machining and pure machining approaches for producing a steel blade. The authors observed that the integrated approach had higher material utilisation, leading to material savings of approximately 60% over pure machining. Additionally, the additive-subtractive approach was more energy efficient, achieving an energy saving of 34% compared to pure machining.

Priarone et al. [76] conducted a cradle-to-grave LCA to assess the environmental effectiveness of using WAAM for repairing steel (H13) mould inserts used in the casting process. The study found that the AM-based repair approach was more eco-friendly than the conventional substitution-based approach. Specifically, the AM-based repair strategy reduced the life-cycle energy consumption by 16.1% and carbon emissions by 20.2% compared to traditional repair methods. These findings highlight how AM supports the fundamental principles of the circular economy by enabling the repair and extension of product lifespan.

3.4. Other MAM technologies

Raoufi et al. [84] applied cradle-to-gate LCA to estimate the environmental impact of stainless steel (316L) plates used in microscale chemical reactors. They compared the sustainability performance of two manufacturing methods: Metal Injection Moulding (MIM) and BJ. The results of the environmental impact assessment showed that for low annual production volumes (up to 1000 reactors), BJ had lower Cumulative Energy Demand (CED) and Global Warming Potential (GWP) than MIM. However, for high production volume, MIM was more environmentally friendly than BJ.

4. Economics of MAM

4.1. Early Economic Models of AM

It is important to assess economic viability of MAM to understand its potential for adding business value. The economic viability of a manufacturing process can be measured by its ability to reduce costs or shorten production time. Many research studies have been conducted to evaluate the production cost and time of MAM techniques compared to CM methods. Reliable cost models that can forecast the cost of AMed parts are essential to inform investment decisions. CM cost models are limited to material and labour costs and are unsuitable for modern manufacturing systems involving high capital investment. Therefore, cost models accounting for investment, overheads, energy costs, etc. are needed for MAM methods, as shown in Figure 5. The cost models of MAM techniques have evolved from simple generic models considering material and labour costs to more comprehensive models accounting for machine and maintenance costs, process-based defects, and pre- and post-printing operations.

Earlier economic studies of AM methods focused on evaluating the economic performance of AM methods for rapid tooling applications. These studies proved that AM techniques can produce durable prototypes within a short time, leading to significant economic value in reducing the time to market and expediting the development cycle of new products [85,86]. Some examples of cost models relevant to MAM methods are those presented by Hopkinson and Dickens [87] and Ruffo et al. [88,89]. Hopkinson and Dickens [87] presented a cost model for the SLS process encompassing machine, labour, and material costs. The modelled costs of the part assumed that the machine produces one part consistently for one year. The costs of the post-building operations were not included as the surface finish of the produced part was assumed to be of good standard, requiring no finishing operations. The researchers found that SLS was more cost-effective than Fused Deposition Modelling (FDM) and stereolithography. The research highlighted that material costs had a significant impact on the cost model. The study concluded that SLS was a more viable option than injection moulding for a production volume up to around 14000. Ruffo et al. [88] proposed a cost model of the SLS process that included direct costs (raw materials costs) and indirect costs (the machine tool, administrative and production overheads, and labour costs). The model did not consider the energy cost of the machine or costs associated with pre- and post-processing operations. The model used a packing ratio factor, which represents the utilization ratio of the build space, to calculate the costs of producing multiple copies of the same part. Machine cost was found to be the most significant factor, accounting for around 38% of the total cost per part. The part size and packing ratio had a notable impact on the cost model. The results demonstrated that the cost per part decreases as the production volume (the number of manufactured parts) increases. In another work, Ruffo and [89] enhanced their earlier cost model by expanding it to accommodate the production of multiple parts with different geometries. The main goal of incorporating parts with different geometries in the same build job was to increase the build packing ratio and, consequently, lower the part cost. Their research demonstrated that cost savings were achievable by adopting this mixed production method.

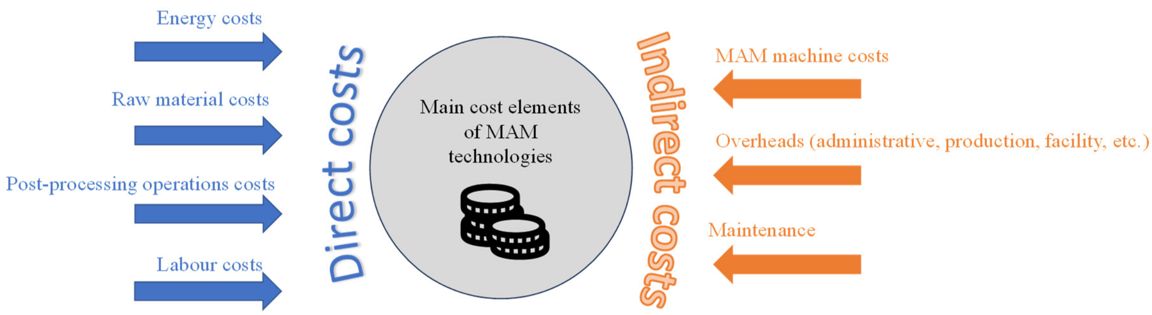


Figure 5. Main cost elements of MAM technologies.

4.2. PBF

Many studies compared the economic performance of PBF and CM processes in producing usable metallic products, focusing on cost and production time. Atzeni and Salmi [35] compared the economic performance of PBF-LB/M and High Pressure Die Casting (HPDC) processes for manufacturing landing gear structures made of aluminium alloy (AlSi10Mg). The part redesign was conducted to exploit the 'freeform fabrication' capability of AM. The cost analysis showed that the die in HPDC and the machine tool in PBF-LB/M contributed the most to the overall cost of each process. It was estimated that around 90% of the PBF-LB/M-manufactured part cost was associated with the depreciation of the AM system due to its high initial costs. The research concluded that PBF-LB/M is an economic manufacturing method for small to medium-batch productions. For a batch size of less than 42, the cost of the PBF-LB/M -manufactured structure was less than the HPDC-manufactured one. The study also revealed that PBF-LB/M can reduce costs and shorten the time from design to manufacturing by eliminating delays associated with die tooling preparation. Guarino et al. [54] compared the economic performance of PBF-LB/M and CO_2 Laser Cutting (LC) processes for flat washer production. They found that PBF-LB/M was less cost-effective than LC. They attributed the high production cost of PBF-LB/M to the significant consumption of the inert gas during the process. The production capacity of PBF-LB/M was 217 times less than that of LC, confirming that PBF-LB/M is only suitable for small-volume production. Mami et al. [59] found that the production costs of PBF-LB/M were higher than Computer Numerical Control (CNC) machining for fabricating a titanium aeroplane doorstop. Bouquet et al. [90] compared the production times of steel spur gear manufactured using milling, Wire-cut Electrical Discharge Machine (WEDM), and PBF-LB/M techniques. They found that milling was the fastest route, completing the gear manufacturing within 14.25 h. PBF-LB/M, with 17 h production time, was the second fastest option, while WEDM, with 22 h, was the slowest method. Hällgren et al.[91] compared cost- and time-effectiveness of PBF-LB/M with High Speed Machining (HSM). The evaluation considered three different materials: steel, titanium and aluminium, as well as eight parts that can be cut from rod blanks. The results showed that manufacturing using PBF-LB/M is more expensive than milling, even for a production scale of one unit. The cost of PBF-LB/M can increase further if the printed parts need post-processing machining. Parts with simple designs and made from soft (easy-to-cut) materials are more cost-effective to be manufactured by CM rather than AM. The study found that PBF-LB/M could be a more economical production option than machining if the printing speed could be increased by eight times. It also highlighted that eliminating post-printing requirements and reducing the material requirements through lightweight design are possible routes to reduce the cost of PBF-LB/Med parts. In a similar work, Kamps et al. [36] found that machine equipment and powder costs are the main drivers of the high cost of the PBF-LB/M process. They reported that the lightweight design that enables less material consumption and higher material utilisation is essential to reduce the cost of the PBF-LB/Med part. Manogharan et al. [92] constructed cost models to compare the costs of manufacturing titanium (Ti6Al4V) parts using subtractive CNC milling and hybrid PBF-EB/M-machining strategies. The researchers found that despite the higher material utilisation of the hybrid approach, its production cost was higher than that of the milling approach for a batch size of four. The production cost of the hybrid approach decreased by increasing the batch size due to high fixed costs for each run. The study suggested that the hybrid approach is advantageous for parts made of expensive and hard-to-machine materials, while the subtractive approach is more economical for cheap and easy-to-machine materials. It also identified that the economic viability of the hybrid approach could be enhanced by reducing the production time, feedstock material cost, and operating costs of PBF-EB/M.

Constructing cost models that suit the nature of the PBF processes was an endeavour of many studies. Baumers et al. [93] constructed a cost model of the PBF-LB/M process, considering the indirect costs arising from labour costs, machine costs, administrative and production overheads, as well as direct costs, including raw material and energy costs. The authors reported that a build with different parts and maximum utilization capacity of the build volume resulted in cost reduction and lower energy consumption, leading to improved overall sustainability performance. Rickenbacher et al. [94] presented a cost model of the PBF-LB/M process, taking into account costs associated with pre- and post-processing operations. The model is based on a build job containing multiple parts with identical or different geometries. The work showed that the simultaneous printing of multiple parts can reduce machine set-up time and powder coating time per printed part, thereby lowering the overall cost of the manufactured part. Baumers et al. [95] developed a production cost model of PBF-EB/M and PBF-LB/M processes. Their model indicated that machine productivity is a key cost driver for both processes. The authors observed that specific costs of the two MAM processes were high and greater than conventional manufacturing processes, such as injection moulding and machining. The specific cost of PBF-LB/M was greater than that of PBF-EB/M due to its lower deposition rate. The study suggested that as AM systems continue to advance, process productivity will improve, leading to cost reductions. Baumers et al. [96] presented a cost model for the PBF-LB/M process that considered the cost impact of the print failure and post-build operations, including the removal of the anchor structures, surface improvement, washing, and inspection. The study proved that the capacity utilization of the build space is an important factor in the cost of the part. It also showed that the cost of a part in a mixed build at full utilization capacity was lower than that in a build with a single geometry but lower utilization capacity. The research also highlighted that cost savings associated with the use phase of AM-designed and built parts may outweigh that of the manufacturing phase. Colosimo et al. [97] demonstrated the impact of in-situ monitoring capabilities on AM production costs by developing a cost model that considered the cost implication of process defectiveness. The model included costs associated with pre- and post-processing operations, the building process, and raw materials. The cost of in-situ monitoring tools was reflected in the model by introducing extra equipment costs. The authors found that using the in-situ monitoring tool resulted in economic benefits for high-value metal products made of expensive materials and required long building time. The effectiveness of the in-situ monitoring tool stemmed from its capability to provide early defective process interruption, thus reducing the scarp rate, material waste, and the overall part cost. Table 3 summarizes the main cost drivers of PBF-LB/M as the most explored MAM process in the literature.

The economic performance of PBF-LB/M process in manufacturing tooling for other CM processes was a topic for some studies. Vasco et al. [98] considered the machine, material, and energy costs to assess the economic viability of PBF-LB/M to produce metallic inserts for the injection moulding process. The authors found that PBF-LB/Med inserts enhanced both the quality and productivity of the injection moulding process because they produced high-quality parts with less scrap rate and shortened the overall cycle time of the injection process. The study revealed that the quality and productivity enhancement achieved by PBF-LB/Med inserts reduced the energy consumption of the injection process. However, despite energy savings, the part cost manufactured using a mould with PBF-LB/Med inserts was greater than that manufactured using conventional tooling due to the high initial tool cost of the PBF-LB/M system. Wiedenegger et al. [99] demonstrated the economic value of using PBF-LB/M to manufacture die-casting inserts with conformal cooling channels in improving the heat dissipation process and reducing the scrap rate of the HPDC process. The results showed that PBF-LB/Med inserts had a scrap rate of 3.74%, less than 7.1% of conventional inserts. Additionally, PBF-LB/Med inserts had the potential to reduce the cycle time and increase the tool life of the HPDC process. The study highlighted that despite the high initial cost of PBF-LB/M equipment, the positive outcomes in terms of enhanced heat dissipation, improved part quality, and reduced scrape rate can generate significant cost savings.

Table 3. Main cost drivers for PBF-LB/M process.

MAM Process	Cost Drivers	Ref
PBF-LB/M	Machine cost.	[35–37]
	Feedstock.	[36,92]
	Operation and labour.	[37,92]
	Machine productivity (deposition rate).	[95]
	Utilization capacity of the building platform.	[96]

4.3. DED

Dias et al. [73] developed a cost model to estimate the economic viability of WAAM for producing metallic parts as an alternative to machining processes. The study found that material cost, with a 55% share of total production costs per part, was the main cost driver of the WAAM process. The cost model confirmed the economic viability of WAAM, predicting a 34% cost reduction when WAAM is used instead of machining. Priarone et al. [27] found that the WAAM process had a lower total cost and production time than machining for fabricating parts with small solid-to-cavity ratios. The economic performance of WAAM, in terms of production costs and efficiency, decreased as the solid-to-cavity ratio of the parts increased. The study showed that machining processes had higher production efficiency and lower costs than WAAM for parts with high solid-to-cavity ratios. In another work, Priarone et al. [75] compared the economic performance of different WAAMed and machined parts. The authors employed product cost and manufacturing time as economic performance metrics. The study found that manufacturing time and costs depend on the part's material. WAAM and machining exhibited comparable economic metrics for manufacturing titanium and aluminium parts. However, the manufacturing cost and time of WAAMed steel parts were greater than those of machined parts. Kokare et al. [37] conducted LCC to compare the production costs using PBF-LB/M, WAAM, and CNC milling for manufacturing a marine propeller. The findings revealed that WAAM was the most cost-effective production route for the propeller compared to CNC and PBF-LB/M. The study identified that the high cost of the PBF-LB/M machine tool caused the high production cost for this process. In a similar study, Kokare et al. [71] compared the economic performance of WAAM, PBF-LB/M, and CNC for manufacturing a single steel wall. The work showed that CNC and PBF-LB/M were the most and least economical manufacturing options, respectively. It also highlighted that the machine and labour costs were the primary cost drivers of the PBF-LB/M process.

Mandolini et al. [100] constructed a cost model for the DED-LB/M process to assess the production costs from the machine set-up to removing the built part. The model ignored the costs of the post-processing operations and only accounted for material, consumables, labour, equipment, and energy costs. The study found that the machine and material costs were the most influencing factors in the cost model.

4.4. Other MAM Technologies

The economics of other MAM methods, such as BJ, have received limited studies, which proposed some preliminary cost models of these processes. Raoufi et al. [84] compared the relative cost of microreactor steel plates fabricated by BJ and MIM processes. The cost assessment revealed that the BJ-fabricated plates were more expensive than the MIM-fabricated ones. Capital tooling and labour costs were the key cost drivers of the BJ process. The MIM process had lower capital tooling costs and shorter cycle times to make the product. In a similar work, Manoharan et al. [7] conducted a comparative cost analysis of BJ and PBF-LB/M processes for fabricating microreactor stainless steel plates. The authors developed cost models, accounting for raw materials, facility, tool, maintenance, labour, utilities, and consumables expenses. The results suggested that BJ was more cost-effective than PBF-LB/M by around 40% for an annual production of 1000 reactors. Furthermore, they indicated that the good economic performance of the BJ process was due to lower capital investments and shorter cycle times for producing the parts.

5. Environmental and Economic Advantages and Limitations of MAM

Table 4 summarizes the key environmental and economic advantages and limitations of MAM. From an economic point of view, cost models developed in the literature confirmed that MAM technologies are more expensive than CM methods, such as machining, according to cost models developed in the literature. The principal causes of the low economic performance of some MAM technologies are the high costs of machine tools and feedstock materials, and slow process speed. For example, the cost of powder feedstock used in PBF and DED processes is one or two orders of magnitude higher than that of wrought stock used in machining. For successful MAM building, powder feedstock must meet specific morphology and size requirements (they must be small-sized particles with a spherical-like shape). Such powder requirements are only achievable by using advanced powder atomization processes. In general, MAM processes with wire feedstock, such as WAAM, are more cost-effective than MAM with powder feedstock. The slow process speed is another reason affecting the economic performance of MAM. The slow process speed stems from the low material deposition rate of MAM and it causes an increase in indirect time-dependent costs, increasing the cost of the manufactured unit [95]. DED processes have substantially higher material deposition rates (0.5 kg/h for DED-LB/M to 10 kg/h for WAAM [101]) than PBF processes (0.1 kg/h for PBF-LB/M [102]) and PBF-EB/M (0.041–0.13 kg/h [40]), resulting in better economic performance for DED over other PBF processes. The typical rate of CM processes, such as machining, can reach 100 kg/h which is substantially greater than MAM processes [95]. The productivity limitation of MAM processes renders them unsuitable for medium- to high-volume production and only favourable for small-volume production. Despite being an expensive option, MAM still yields some economic benefits in achieving higher production efficiency and shortening production times compared to CM processes that require custom tools, such as inserts, dies, and punches. MAM builds the part directly from a 3D CAD model, reducing the setup and changeover times and the number of assemblies.

From the environmental perspective, using MAM in industrial sectors provides multiple avenues for environmental benefits but also involves some caveats. On the positive side, MAM processes have higher material efficiency and lower material waste than subtractive processes, such as machining, due to the layer-by-layer building approach. Also, MAM processes require no specific tooling, such as those used in casting and forging processes, reducing the carbon footprint associated with preparing such tooling. The environmental caveats of MAM processes stem from different sources. Some MAM processes, such as PBF-LB/M and DED-LB/M, use high-intensity lasers that may increase their energy demands. Additionally, the powder feedstock of many MAM processes may increase overall energy consumption and environmental impact due to the powder preparation stages. The MAM-accepted powder feedstock is produced through Gas Atomization (GA) processes, which are energy-intensive processes with CED of 77.94–112.43 MJ/kg and GWP of 4.61–6.69 kg CO_2-eq [103]. The contribution of GA to the overall environmental impact of MAM depends on the specific type of MAM process and its material efficiency. For instance, Ehmsen et al. [104] found that the powder production stage can account for up to 55% of the total environmental impact in the high-speed DED-LB/M process. Similarly, Serres et al. [68] reported that approximately 90 % of the environmental impact in the DED-LB/M process arises from the powder production stage. Wang et al. [78] noted that powder production has the greatest environmental impact among all stages of PBF-LB/M. Peng et al. [50] indicated that the powder production stage is responsible for approximately 44.13% to 46.38% of the environmental impact associated with PBF-LB/M. The poor surface finish of MAM-fabricated parts and their need for post-processing treatments are other sources of environmental impact. Many literature studies indicated that the specific energy consumption of MAM is one or two orders of magnitude higher than CM processes [20,105,106].

One aim of this paper is to identify the MAM production contexts that are environmentally and economically valuable. Table 5 compares the quality, environmental, and economic indicators of different MAM technologies, highlighting production scenarios in which they can be beneficial. Based on the current landscape of MAM technologies, market needs, and economic and environmental constraints, it is evident that MAM is both economically viable and environmentally friendly for low-volume production of high-value parts with intricate geometries and hard-to-machine materials that are costly and not easy to manufacture by CM methods. Manufacturing enterprises can achieve a more sustainable business model by adopting MAM technologies in parallel with their CM processes and using them for job orders of customized parts with complex geometry and low quantities.

Table 4. Environmental and economic advantages and limitations of MAM.

	Advantages	Limitations
Environmental	• MAM processes have high material utilisation due to the layer-by-layer building approach, resulting in less resource consumption compared to CM processes. • MAM processes are environmentally friendly processes for manufacturing lightweight products with optimized geometries. • MAM processes can reduce the environmental burden when used for repair applications • Wire-based MAM processes, such as WAAM, have low energy demand.	• Laser-based MAM processes, such as PBF-LB/M and DED, have high specific energy consumption due to the use of the laser beam as a heat source. • Powder feedstock used in PBF-LB/M, PBF-EB/M, and DED-LB/M has a significant carbon footprint due to the energy-intensive gas atomization process required to produce MAM-accepted feedstock. • Parts produced by MAM processes tend to have rough surfaces, requiring post-building operations that may have a high environmental impact.
Economic	• MAM processes are more cost-effective than CM for manufacturing geometrically complex parts in low quantities. • MAM processes enable the production of high-value parts with multiple functionalities and better utility. • MAM processes are more cost-effective than machining for manufacturing hard-to-machine materials. • MAM-based repair is more economical than the conventional repair approach.	• High specific cost of feedstock, particularly in MAM technologies that use powder (PBF-LB/M, PBF-EB/M, and DED-LB/M). • Some MAMs, such as PBF-LB/M, have low material deposition rates, resulting in slow process productivity. • The use of inert gas in the building chamber of some MAM processes, such as PBF-LB/M, DED, and WAAM, increases the specific cost of the produced part. • Parts produced by MAM processes may require significant and expensive post-processing operations due to rough surface finish.

Table 5. Comparison of quality, environmental, and economic indicators of different MAM technologies.

MAM	Quality Indicators		Environmental Indicator	Economic Indicators		Feasible Production Scenario
	Surface Roughness	Dimensional Accuracy	Energy Consumption	Process Speed	Feedstock Cost	
PBF-LB/M	Low	High	High	Low	High	Small-scale production of small parts with customized or complex shape.
PBF-EB/M	Medium	Medium	Medium	Medium	High	Small-scale production of complex parts with medium resolution.
DED-LB/M	High	Low	High	High	High	Repairing and revamping damaged large parts.
WAAM	High	Low	Low	High	Low	Manufacturing large parts with medium shape complexity and low resolution.

6. Conclusions

In response to the urgent need for sustainable manufacturing processes, there is a growing focus on developing manufacturing strategies that prioritize environmental sustainability alongside economic profitability. Additive Manufacturing (AM) technologies, particularly Metal Additive Manufacturing (MAM), are gaining attention in this context. With sustainability in mind, economic profitability is no longer the sole determining factor for a manufacturing option. The capability of a manufacturing process to yield environmental sustainability is another key indicator in the decision-making matrix. MAM continues to grow as a manufacturing option for a wide range of industrial parts; therefore, understanding its environmental and economic impacts is gaining momentum. Thus, this paper conducted a comprehensive literature review on the environmental and economic performances of MAM to evaluate its remits in the sustainable/green manufacturing realm. The main recommendations that can be drawn from this review are:

- The environmental and economic performances of MAM are highly context-dependent and sensitive to multiple interconnected factors, such as geometrical features, feedstock type, production volume, dimensional tolerances, and surface finish requirements.
- Comprehensive Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) analysis are indispensable tools for manufacturing firms to fully realize the ecological and economic benefits of MAM compared to their current manufacturing methods.
- Leveraging the free-form fabrication capability of MAM, maximizing the utilization capacity of the build space, optimizing the process parameters, improving process productivity, and minimizing post-processing treatments are essential for enhancing the cost-effectiveness and reducing the environmental burden of MAM processes.

Although recent studies enabled a fair understanding of the environmental and economic impacts of MAM, there are several areas that still require further investigation. The environmental and economic performance of some MAMs, such as BJ and LAB-DED, have not received enough attention. Therefore, they require further LCC and LCA studies to establish their sustainability and economic merits. Also, existing literature on the sustainability of MAM process parameters often neglects quality or mechanical performance assessments of the produced parts. Future research studies should integrate environmental, economic, and quality assessments to ensure the production of high-quality, environmentally friendly, and cost-effective parts that meet the industry requirements.

As a final remark, it is anticipated that MAM will become more competitive in the future, particularly with technological advancements that enable reducing costs and increasing the energy efficiency of MAM-acceptable feedstock materials and systems.

Author Contributions

A.B: conceptualization, investigation, methodology, data curation, visualization, writing – original draft, writing – review & editing; A.A: conceptualization, investigation, methodology, writing – review & editing; J.R.: conceptualization, investigation, methodology, writing – review & editing; A.V.: conceptualization, investigation, methodology, writing – review & editing; A.A.: conceptualization, investigation, methodology, writing – review & editing.

Funding

This research received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Not applicable.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Ritchie, H.; Rosado, P.; Roser, M. Breakdown of Carbon Dioxide, Methane and Nitrous Oxide Emissions by Sector. Available online: https://ourworldindata.org/emissions-by-sector#article-citation (accessed on 1 April 2025).
2. Zhang, S.; Wang, X.; Xu, J.; et al. Green Manufacturing for Achieving Carbon Neutrality Goal Requires Innovative Technologies: A Bibliometric Analysis from 1991 to 2022. *J. Environ. Sci.* **2024**, *140*, 255–269. https://doi.org/10.1016/j.jes.2023.08.016.
3. Bui, T.; Tuong, T.; Nguyen, V.; et al. International Journal of Production Economics Green Manufacturing Performance Improvement under Uncertainties: An Interrelationship Hierarchical Model. *Int. J. Prod. Econ.* **2024**, *268*, 109117. https://doi.org/10.1016/j.ijpe.2023.109117.
4. Watari, T.; Nansai, K.; Nakajima, K. Major Metals Demand, Supply, and Environmental Impacts to 2100: A Critical Review. *Resour. Conserv. Recycl.* **2021**, *164*, 105107. https://doi.org/10.1016/j.resconrec.2020.105107.
5. Punj, N.; Ahmi, A.; Tanwar, A.; et al. Mapping the Field of Green Manufacturing: A Bibliometric Review of the Literature and Research Frontiers. *J. Clean. Prod.* **2023**, *423*, 138729. https://doi.org/10.1016/j.jclepro.2023.138729.
6. Javaid, M.; Haleem, A.; Singh, R.P.; et al. Role of Additive Manufacturing Applications towards Environmental Sustainability. *Adv. Ind. Eng. Polym. Res.* **2021**, *4*, 312–322. https://doi.org/10.1016/J.AIEPR.2021.07.005.
7. Manoharan, S.; Lee, K.; Freiberg, L.; et al. Comparing the Economics of Metal Additive Manufacturing Processes for Micro-Scale Plate Reactors in the Chemical Process Industry. *Procedia Manuf.* **2019**, *34*, 603–612. https://doi.org/10.1016/j.promfg.2019.06.168.
8. Agnusdei, L.; Del Prete, A. Additive Manufacturing for Sustainability: A Systematic Literature Review. *Sustain. Futur.* **2022**, *4*, 100098. https://doi.org/10.1016/j.sftr.2022.100098.
9. Kumar, R.; Kumar, M.; Chohan, J.S. The Role of Additive Manufacturing for Biomedical Applications: A Critical Review. *J. Manuf. Process.* **2021**, *64*, 828–850.
10. Chhaya, M.P.; Poh, P.S.P.; Balmayor, E.R.; et al. Additive Manufacturing in Biomedical Sciences and the Need for Definitions and Norms. *Expert Rev. Med. Devices* **2015**, *12*, 537–543. https://doi.org/10.1586/17434440.2015.1059274.
11. Kaur, I.; Singh, P. State-of-the-Art in Heat Exchanger Additive Manufacturing. *Int. J. Heat Mass Transf.* **2021**, *178*, 121600. https://doi.org/10.1016/j.ijheatmasstransfer.2021.121600.
12. Charles, A.; Hofer, A.; Elkaseer, A.; et al. Additive Manufacturing in the Automotive Industry and the Potential for Driving the Green and Electric Transition. In Proceedings of the 8th International Conference of Sustainable Design and Manufacturing (KES-SDM 2021), Online, 15–17 September 2021; Springer: Singapore, 2022; Volume 262, pp. 339–346. https://doi.org/10.1007/978-981-16-6128-0_32.
13. Mohanavel, V.; Ashraff Ali, K.S.; Ranganathan, K.; et al. The Roles and Applications of Additive Manufacturing in the Aerospace and Automobile Sector. *Mater. Today Proc.* **2021**, *47*, 405–409. https://doi.org/10.1016/j.matpr.2021.04.596.
14. Blakey-Milner, B.; Gradl, P.; Snedden, G.; et al. Metal Additive Manufacturing in Aerospace: A Review. *Mater. Des.* **2021**, *209*, 110008. https://doi.org/10.1016/J.MATDES.2021.110008.
15. Ambrosi, A.; Moo, J.G.S.; Pumera, M. Helical 3D-Printed Metal Electrodes as Custom-Shaped 3D Platform for Electrochemical Devices. *Adv. Funct. Mater.* **2016**, *26*, 698–703. https://doi.org/10.1002/ADFM.201503902.
16. Hashemi, S.M.H.; Babic, U.; Hadikhani, P.; et al. The Potentials of Additive Manufacturing for Mass Production of Electrochemical Energy Systems. *Curr. Opin. Electrochem.* **2020**, *20*, 54–59. https://doi.org/10.1016/J.COELEC.2020.02.008.
17. Sun, C.; Wang, Y.; McMurtrey, M.D.; et al. Additive Manufacturing for Energy: A Review. *Appl. Energy* **2021**, *282*, 116041. https://doi.org/10.1016/J.APENERGY.2020.116041.
18. Gulzar, U.; Glynn, C.; O’Dwyer, C. Additive Manufacturing for Energy Storage: Methods, Designs and Material Selection for Customizable 3D Printed Batteries and Supercapacitors. *Curr. Opin. Electrochem.* **2020**, *20*, 46–53. https://doi.org/10.1016/j.coelec.2020.02.009.
19. Baroutaji, A.; Arjunan, A.; Robinson, J.; et al. Developments and Prospects of Additive Manufacturing for Thermoelectric Materials and Technologies. *Sustain. Mater. Technol.* **2024**, *41*, e01008. https://doi.org/10.1016/j.susmat.2024.e01008.
20. Kellens, K.; Baumers, M.; Gutowski, T.G.; et al. Environmental Dimensions of Additive Manufacturing: Mapping Application Domains and Their Environmental Implications. *J. Ind. Ecol.* **2017**, *21*, S49–S68. https://doi.org/10.1111/jiec.12629.
21. *ISO/ASTM 52900:2015*; Standard Terminology for Additive Manufacturing—General Principles-Terminology. ISO: Geneva, Switzerland, 2015.
22. Tofail, S.A.M.; Koumoulos, E.P.; Bandyopadhyay, A.; et al. Additive Manufacturing: Scientific and Technological Challenges, Market Uptake and Opportunities. *Mater. Today* **2018**, *21*, 22–37. https://doi.org/10.1016/J.MATTOD.2017.07.001.
23. Herzog, D.; Seyda, V.; Wycisk, E.; et al. Additive Manufacturing of Metals. *Acta Mater.* **2016**, *117*, 371–392. https://doi.org/10.1016/j.actamat.2016.07.019.
24. Baroutaji, A.; Arjunan, A.; Robinsion, J.; et al. Metallic Meta-Biomaterial as Biomedical Implants. *Encycl. Smart Mater.* **2022**, 70–80. https://doi.org/10.1016/B978-0-12-815732-9.00117-0.

25. Körner, C. Additive Manufacturing of Metallic Components by Selective Electron Beam Melting—A Review. *Int. Mater. Rev.* **2016**, *61*, 361–377. https://doi.org/10.1080/09506608.2016.1176289.
26. Ahn, D.G. *Directed Energy Deposition (DED) Process: State of the Art*; Korean Society for Precision Engineering: Seoul, Republic of Korea, 2021. https://doi.org/10.1007/s40684-020-00302-7.
27. Priarone, P.C.; Campatelli, G.; Montevecchi, F.; et al. A Modelling Framework for Comparing the Environmental and Economic Performance of WAAM-Based Integrated Manufacturing and Machining. *CIRP Ann.* **2019**, *68*, 37–40. https://doi.org/10.1016/j.cirp.2019.04.005.
28. Costello, S.C.A.; Cunningham, C.R.; Xu, F.; et al. The State-of-the-Art of Wire Arc Directed Energy Deposition (WA-DED) as an Additive Manufacturing Process for Large Metallic Component Manufacture. *Int. J. Comput. Integr. Manuf.* **2023**, *36*, 469–510. https://doi.org/10.1080/0951192X.2022.2162597.
29. Ziaee, M.; Crane, N.B. Binder Jetting : A Review of Process, Materials , and Methods. *Addit. Manuf.* **2019**, *28*, 781–801. https://doi.org/10.1016/j.addma.2019.05.031.
30. Chowdhury, S.; Yadaiah, N.; Prakash, C.; et al. Laser Powder Bed Fusion: A State-of-the-Art Review of the Technology, Materials, Properties & Defects, and Numerical Modelling. *J. Mater. Res. Technol.* **2022**, *20*, 2109–2172. https://doi.org/10.1016/j.jmrt.2022.07.121.
31. Baroutaji, A.; Arjunan, A.; Singh, G.; et al. Crushing and energy absorption properties of additively manufactured concave thin-walled tubes. *Results Eng.* **2022**, *14*, 100424. https://doi.org/10.1016/J.RINENG.2022.100424.
32. Baroutaji, A.; Arjunan, A.; Stanford, M.; et al. Deformation and energy absorption of additively manufactured functionally graded thickness thin-walled circular tubes under lateral crushing. *Eng. Struct.* **2021**, *226*, 111324. https://doi.org/10.1016/j.engstruct.2020.111324.
33. Gao, C.; Wolff, S.; Wang, S. Eco-Friendly Additive Manufacturing of Metals: Energy Efficiency and Life Cycle Analysis. *J. Manuf. Syst.* **2021**, *60*, 459–472. https://doi.org/10.1016/j.jmsy.2021.06.011.
34. Baroutaji, A.; Arjunan, A.; Robinson, J.; et al. Additive Manufacturing for Proton Exchange Membrane (PEM) Hydrogen Technologies: Merits, Challenges, and Prospects. *Int. J. Hydrogen Energy* **2023**, *52*, 561–584. https://doi.org/10.1016/j.ijhydene.2023.07.033.
35. Atzeni, E.; Salmi, A. Economics of Additive Manufacturing for End-Usable Metal Parts. *Int. J. Adv. Manuf. Technol.* **2012**, *62*, 1147–1155. https://doi.org/10.1007/s00170-011-3878-1.
36. Kamps, T.; Lutter-Guenther, M.; Seidel, C.; et al. Cost- and Energy-Efficient Manufacture of Gears by Laser Beam Melting. *CIRP J. Manuf. Sci. Technol.* **2018**, *21*, 47–60. https://doi.org/10.1016/j.cirpj.2018.01.002.
37. Kokare, S.; Oliveira, J.P.; Godina, R. A LCA and LCC Analysis of Pure Subtractive Manufacturing, Wire Arc Additive Manufacturing, and Selective Laser Melting Approaches. *J. Manuf. Process.* **2023**, *101*, 67–85. https://doi.org/10.1016/j.jmapro.2023.05.102.
38. Oshida, Y. Fabrication Technologies. In *Bioscience and Bioengineering of Titanium Materials*; Elsevier: Amsterdam, The Netherlands, 2013; pp 303–340. https://doi.org/10.1016/B978-0-444-62625-7.00010-8.
39. Zhang, L.C.; Liu, Y.; Li, S.; et al. Additive Manufacturing of Titanium Alloys by Electron Beam Melting: A Review. *Adv. Eng. Mater.* **2018**, *20*, 1700842. https://doi.org/10.1002/adem.201700842.
40. Lunetto, V.; Galati, M.; Settineri, L.; et al. Unit Process Energy Consumption Analysis and Models for Electron Beam Melting (EBM): Effects of Process and Part Designs. *Addit. Manuf.* **2020**, *33*, 101115. https://doi.org/10.1016/j.addma.2020.101115.
41. Gruber, S.; Grunert, C.; Riede, M.; et al. Comparison of Dimensional Accuracy and Tolerances of Powder Bed Based and Nozzle Based Additive Manufacturing Processes. *J. Laser Appl.* **2020**, *32*. https://doi.org/10.2351/7.0000115.
42. Zhong, C.; Gasser, A.; Backes, G.; et al. Laser Additive Manufacturing of Inconel 718 at Increased Deposition Rates. *Mater. Sci. Eng. A* **2022**, *844*, 143196. https://doi.org/10.1016/j.msea.2022.143196.
43. Cooke, S.; Ahmadi, K.; Willerth, S.; et al. Metal Additive Manufacturing : Technology , Metallurgy and Modelling. *J. Manuf. Process.* **2020**, *57*, 978–1003. https://doi.org/10.1016/j.jmapro.2020.07.025.
44. Wu, B.; Pan, Z.; Ding, D.; et al. A Review of the Wire Arc Additive Manufacturing of Metals: Properties, Defects and Quality Improvement. *J. Manuf. Process.* **2018**, *35*, 127–139. https://doi.org/10.1016/j.jmapro.2018.08.001.
45. Cunningham, C.R.; Flynn, J.M.; Shokrani, A.; et al. Invited Review Article : Strategies and Processes for High Quality Wire Arc Additive Manufacturing. *Addit. Manuf.* **2018**, *22*, 672–686. https://doi.org/10.1016/j.addma.2018.06.020.
46. Li, M.; Du, W.; Elwany, A.; et al. Metal Binder Jetting Additive Manufacturing : A Literature Review. *J. Manuf. Sci. Eng. Trans. ASME* **2020**, *142*, 090801. https://doi.org/10.1115/1.4047430/1084395.
47. Liu, Z.; Jiang, Q.; Zhang, Y.; et al. Sustainability of 3D Printing: A Critical Review and Recommendations. In Proceedings of the ASME 2016 11th International Manufacturing Science and Engineering Conference, Blacksburg, VA, USA, 27 June–1 July 2016. https://doi.org/10.1115/MSEC2016-8618.
48. *ISO 14040:2006*; Environmental Management—Life Cycle Assessment—Principles and Framework. International Organization for Standardization: Geneva, Switzerland, 2006.
49. Ingarao, G.; Priarone, P.C.; Deng, Y.; et al. Environmental Modelling of Aluminium Based Components Manufacturing

Routes: Additive Manufacturing versus Machining versus Forming. *J. Clean. Prod.* **2018**, *176*, 261–275. https://doi.org/10.1016/j.jclepro.2017.12.115.

50. Peng, T.; Wang, Y.; Zhu, Y.; et al. Life Cycle Assessment of Selective-Laser-Melting-Produced Hydraulic Valve Body with Integrated Design and Manufacturing Optimization: A Cradle-to-Gate Study. *Addit. Manuf.* **2020**, *36*, 101530. https://doi.org/10.1016/j.addma.2020.101530.
51. Swetha, R.; Siva Rama Krishna, L.; Hari Sai Kiran, B.; et al. Comparative Study on Life Cycle Assessment of Components Produced by Additive and Conventional Manufacturing Process. *Mater. Today Proc.* **2022**, *62*, 4332–4340. https://doi.org/10.1016/j.matpr.2022.04.840.
52. Torres-Carrillo, S.; Siller, H.R.; Vila, C.; et al. Environmental Analysis of Selective Laser Melting in the Manufacturing of Aeronautical Turbine Blades. *J. Clean. Prod.* **2020**, *246*, 119068. https://doi.org/10.1016/j.jclepro.2019.119068.
53. Výtisk, J.; Honus, S.; Kočí, V.; et al. Comparative Study by Life Cycle Assessment of an Air Ejector and Orifice Plate for Experimental Measuring Stand Manufactured by Conventional Manufacturing and Additive Manufacturing. *Sustain. Mater. Technol.* **2022**, *32*, e00431. https://doi.org/10.1016/j.susmat.2022.e00431.
54. Guarino, S.; Ponticelli, G.S.; Venettacci, S. Environmental Assessment of Selective Laser Melting Compared with Laser Cutting of 316L Stainless Steel: A Case Study for Flat Washers' Production. *CIRP J. Manuf. Sci. Technol.* **2020**, *31*, 525–538. https://doi.org/10.1016/j.cirpj.2020.08.004.
55. Ahmad, N.; Enemuoh, E.U. Energy Modeling and Eco Impact Evaluation in Direct Metal Laser Sintering Hybrid Milling. *Heliyon* **2020**, *6*, e03168. https://doi.org/10.1016/j.heliyon.2020.e03168.
56. Faludi, J.; Baumers, M.; Maskery, I.; et al. Environmental Impacts of Selective Laser Melting: Do Printer, Powder, Or Power Dominate? *J. Ind. Ecol.* **2017**, *21*, S144–S156. https://doi.org/10.1111/jiec.12528.
57. Ramadugu, S.; Ledella, S.R.K.; Gaduturi, J.N.J.; et al. Environmental Life Cycle Assessment of an Automobile Component Fabricated by Additive and Conventional Manufacturing. *Int. J. Interact. Des. Manuf.* **2023**, *18*, 847–858. https://doi.org/10.1007/S12008-023-01532-0.
58. Böckin, D.; Tillman, A.M. Environmental Assessment of Additive Manufacturing in the Automotive Industry. *J. Clean. Prod.* **2019**, *226*, 977–987. https://doi.org/10.1016/j.jclepro.2019.04.086.
59. Mami, F.; Revéret, J.; Fallaha, S.; et al. Evaluating Eco-Efficiency of 3D Printing in the Aeronautic Industry. *J. Ind. Ecol.* **2017**, *21*, S37–S48. https://doi.org/10.1111/jiec.12693.
60. Huang, R.; Riddle, M.; Graziano, D.; et al. Energy and Emissions Saving Potential of Additive Manufacturing: The Case of Lightweight Aircraft Components. *J. Clean. Prod.* **2016**, *135*, 1559–1570. https://doi.org/10.1016/j.jclepro.2015.04.109.
61. Priarone, P.C.; Ingarao, G. Towards Criteria for Sustainable Process Selection: On the Modelling of Pure Subtractive versus Additive/Subtractive Integrated Manufacturing Approaches. *J. Clean. Prod.* **2017**, *144*, 57–68. https://doi.org/10.1016/j.jclepro.2016.12.165.
62. Ahmed, A.A.; Nazzal, M.A.; Darras, B.M.; et al. Comparative Sustainability Assessment of Powder Bed Fusion and Solid-State Additive Manufacturing Processes: The Case of Direct Metal Laser Sintering versus Additive Friction Stir Deposition. *Sustain. Mater. Technol.* **2024**, *39*, e00858. https://doi.org/10.1016/j.susmat.2024.e00858.
63. Walachowicz, F.; Bernsdorf, I.; Papenfuss, U.; et al. Comparative Energy , Resource and Recycling Lifecycle Analysis of the Industrial Repair Process of Gas Turbine Burners Using Conventional Machining. *J. Ind. Ecol.* **2017**, *21*, S203–S215. https://doi.org/10.1111/jiec.12637.
64. Tran, C.; Duenas, L.; Misra, S.; et al. Specific Energy Consumption Based Comparison of Distributed Additive and Conventional Manufacturing: From Cradle to Gate Partial Life Cycle Analysis. *J. Clean. Prod.* **2023**, *425*, 138762. https://doi.org/10.1016/j.jclepro.2023.138762.
65. Paris, H.; Mokhtarian, H.; Coatanéa, E.; et al. Comparative Environmental Impacts of Additive and Subtractive Manufacturing Technologies. *CIRP Ann.* **2016**, *65*, 29–32. https://doi.org/10.1016/j.cirp.2016.04.036.
66. Lyons, R.; Newell, A.; Ghadimi, P.; et al. Environmental Impacts of Conventional and Additive Manufacturing for the Production of Ti-6Al-4V Knee Implant: A Life Cycle Approach. *Int. J. Adv. Manuf. Technol.* **2021**, *112*, 787–801. https://doi.org/10.1007/s00170-020-06367-7.
67. Priarone, P.C.; Ingarao, G.; di Lorenzo, R.; et al. Influence of Material-Related Aspects of Additive and Subtractive Ti-6Al-4V Manufacturing on Energy Demand and Carbon Dioxide Emissions. *J. Ind. Ecol.* **2017**, *21*, S191–S202. https://doi.org/10.1111/jiec.12523.
68. Serres, N.; Tidu, D.; Sankare, S.; et al. Environmental Comparison of MESO-CLAD® Process and Conventional Machining Implementing Life Cycle Assessment. *J. Clean. Prod.* **2011**, *19*, 1117–1124. https://doi.org/10.1016/j.jclepro.2010.12.010.
69. Peng, S.; Li, T.; Wang, X.; et al. Toward a Sustainable Impeller Production: Environmental Impact Comparison of Different Impeller Manufacturing Methods. *J. Ind. Ecol.* **2017**, *21*, S216–S229. https://doi.org/10.1111/jiec.12628.
70. Gouveia, J.R.; Pinto, S.M.; Campos, S.; et al. Life Cycle Assessment and Cost Analysis of Additive Manufacturing Repair Processes in the Mold Industry. *Sustainability* **2022**, *14*, 2105. https://doi.org/10.3390/SU14042105.
71. Kokare, S.; Oliveira, J.P.; Santos, T.G.; et al. Environmental and Economic Assessment of a Steel Wall Fabricated by

Wire-Based Directed Energy Deposition. *Addit. Manuf.* **2023**, *61*, 103316. https://doi.org/10.1016/j.addma.2022.103316.
72. Reis, R.C.; Kokare, S.; Oliveira, J.P.; et al. Life Cycle Assessment of Metal Products: A Comparison between Wire Arc Additive Manufacturing and CNC Milling. *Adv. Ind. Manuf. Eng.* **2023**, *6*, 100117. https://doi.org/10.1016/j.aime.2023.100117.
73. Dias, M.; Pragana, J.P.M.; Ferreira, B.; et al. Economic and Environmental Potential of Wire-Arc Additive Manufacturing. *Sustainability* **2022**, *14*. https://doi.org/10.3390/su14095197.
74. Campatelli, G.; Montevecchi, F.; Venturini, G.; et al. Integrated WAAM-Subtractive Versus Pure Subtractive Manufacturing Approaches: An Energy Efficiency Comparison. *Int. J. Precis. Eng. Manuf.-Green Technol.* **2020**, *7*, 1–11. https://doi.org/10.1007/s40684-019-00071-y.
75. Paolo, C.P.; Emanuele, P.; Filomeno, M.; et al. Multi-Criteria Environmental and Economic Impact Assessment of Wire Arc Additive Manufacturing. In *CIRP Annals*; Elsevier: Amsterdam, The Netherlands, 2020; Volume 69, pp. 37–40. https://doi.org/10.1016/j.cirp.2020.04.010.
76. Priarone, P.C.; Campatelli, G.; Catalano, A.R.; et al. Life-Cycle Energy and Carbon Saving Potential of Wire Arc Additive Manufacturing for the Repair of Mold Inserts. *CIRP J. Manuf. Sci. Technol.* **2021**, *35*, 943–958. https://doi.org/10.1016/j.cirpj.2021.10.007.
77. Kellens, K.; Dewulf, W.; Deprez, W.; et al. Environmental Analysis of SLM and SLS Manufacturing Processes. In Proceedings of the LCE 2010 Conference, Hefei, China, 19–21 May 2010; pp. 423–428.
78. Wang, Y.; Peng, T.; Zhu, Y.; et al. A Comparative Life Cycle Assessment of a Selective-Laser-Melting-Produced Hydraulic Valve Body Using Design for Property. *Procedia CIRP* **2020**, *90*, 220–225. https://doi.org/10.1016/j.procir.2020.01.095.
79. Baumers, M.; Tuck, C.; Wildman, R.; et al. Shape Complexity and Process Energy Consumption in Electron Beam Melting: A Case of Something for Nothing in Additive Manufacturing? *J. Ind. Ecol.* **2017**, *21*, S157–S167. https://doi.org/10.1111/jiec.12397.
80. Le, V.T.; Paris, H.; Mandil, G. Environmental Impact Assessment of an Innovative Strategy Based on an Additive and Subtractive Manufacturing Combination. *J. Clean. Prod.* **2017**, *164*, 508–523. https://doi.org/10.1016/j.jclepro.2017.06.204.
81. Kokare, S.; Shen, J.; Fonseca, P.P.; et al. Wire Arc Additive Manufacturing of a High-Strength Low-Alloy Steel Part: Environmental Impacts, Costs, and Mechanical Properties. *Int. J. Adv. Manuf. Technol.* **2024**, 134, 453–475. https://doi.org/10.1007/s00170-024-14144-z.
82. Catalano, A.R.; Pagone, E.; Martina, F.; et al. Wire Arc Additive Manufacturing of Ti-6Al-4V Components: The Effects of the Deposition Rate on the Cradle-to-Gate Economic and Environmental Performance. *Procedia CIRP* **2023**, *116*, 269–274. https://doi.org/10.1016/j.procir.2023.02.046.
83. Shah, I.H.; Hadjipantelis, N.; Walter, L.; et al. Environmental Life Cycle Assessment of Wire Arc Additively Manufactured Steel Structural Components. *J. Clean. Prod.* **2023**, *389*, 136071. https://doi.org/10.1016/j.jclepro.2023.136071.
84. Raoufi, K.; Manoharan, S.; Etheridge, T.; et al. Cost and Environmental Impact Assessment of Stainless Steel Microreactor Plates Using Binder Jetting and Metal Injection Molding Processes. *Procedia Manuf.* **2020**, *48*, 311–319. https://doi.org/10.1016/j.promfg.2020.05.052.
85. Munguía, J.; Ciurana, J.; Riba, C. Neural-Network-Based Model for Build-Time Estimation in Selective Laser Sintering. *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.* **2009**, *223*, 995–1003. https://doi.org/10.1243/09544054JEM1324.
86. King, D.; Tansey, T. Rapid Tooling: Selective Laser Sintering Injection Tooling. *J. Mater. Process. Technol.* **2003**, *132*, 42–48. https://doi.org/10.1016/S0924-0136(02)00257-1.
87. Hopkinson, N.; Dickens, P. Analysis of Rapid Manufacturing - Using Layer Manufacturing Processes for Production. *Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.* **2003**, *217*, 31–40. https://doi.org/10.1243/095440603762554596.
88. Ruffo, M.; Tuck, C.; Hague, R. Cost Estimation for Rapid Manufacturing - Laser Sintering Production for Low to Medium Volumes. *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.* **2006**, *220*, 1417–1427. https://doi.org/10.1243/09544054JEM517.
89. Ruffo, M.; Hague, R. Cost Estimation for Rapid Manufacturing - Simultaneous Production of Mixed Components Using Laser Sintering. *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.* **2007**, *221*, 1585–1591. https://doi.org/10.1243/09544054JEM894.
90. Bouquet, J.; Hensgen, L.; Klink, A.; et al. Fast Production of Gear Prototypes - a Comparison of Technologies. *Procedia CIRP* **2014**, *14*, 77–82. https://doi.org/10.1016/j.procir.2014.03.066.
91. Hällgren, S.; Pejryd, L.; Ekengren, J. Additive Manufacturing and High Speed Machining -Cost Comparison of Short Lead Time Manufacturing Methods. *Procedia CIRP* **2016**, *50*, 384–389. https://doi.org/10.1016/j.procir.2016.05.049.
92. Manogharan, G.; Wysk, R.A.; Harrysson, O.L.A. Additive Manufacturing-Integrated Hybrid Manufacturing and Subtractive Processes: Economic Model and Analysis. *Int. J. Comput. Integr. Manuf.* **2016**, *29*, 473–488. https://doi.org/10.1080/0951192X.2015.1067920.
93. Baumers, M.; Tuck, C.; Wildman, R.; et al. Transparency Built-in: Energy Consumption and Cost Estimation for Additive Manufacturing Baumers et Al. Energy and Cost Estimation for Additive Manufacturing. *J. Ind. Ecol.* **2013**, *17*, 418–431. https://doi.org/10.1111/j.1530-9290.2012.00512.x.
94. Rickenbacher, L.; Spierings, A.; Wegener, K. An Integrated Cost-Model for Selective Laser Melting (SLM). *Rapid Prototyp. J.* **2013**, *19*, 208–214. https://doi.org/10.1108/13552541311312201.

95. Baumers, M.; Dickens, P.; Tuck, C.; et al. The Cost of Additive Manufacturing: Machine Productivity, Economies of Scale and Technology-Push. *Technol. Forecast. Soc. Chang.* **2016**, *102*, 193–201. https://doi.org/10.1016/j.techfore.2015.02.015.
96. Baumers, M.; Beltrametti, L.; Gasparre, A.; et al. Informing Additive Manufacturing Technology Adoption: Total Cost and the Impact of Capacity Utilisation. *Int. J. Prod. Res.* **2017**, *55*, 6957–6970. https://doi.org/10.1080/00207543.2017.1334978.
97. Colosimo, B.M.; Cavalli, S.; Grasso, M. A Cost Model for the Economic Evaluation of In-Situ Monitoring Tools in Metal Additive Manufacturing. *Int. J. Prod. Econ.* **2020**, *223*, 107532. https://doi.org/10.1016/j.ijpe.2019.107532.
98. Vasco, J.; Barreiros, F.M.; Nabais, A.; et al. Additive Manufacturing Applied to Injection Moulding: Technical and Economic Impact. *Rapid Prototyp. J.* **2019**, *25*, 1241–1249. https://doi.org/10.1108/RPJ-07-2018-0179.
99. Wiedenegger, A.; Bruckwilder, J.; Deutsch, C. Ecological and Economic Benefits of Additive Manufacturing in High Pressure Die Casting. *BHM Berg-Und Hüttenmännische Monatshefte* **2021**, *166*, 237–242. https://doi.org/10.1007/s00501-021-01110-5.
100. Mandolini, M.; Sartini, M.; Favi, C.; et al. An Analytical Cost Model for Laser-Directed Energy Deposition (L-DED). Proceedings of the International Joint Conference on Mechanics, Design Engineering & Advanced Manufacturing (JCM 2022), Ischia, Italy, 1–3 June 2022; pp. 993–1004. https://doi.org/10.1007/978-3-031-15928-2_87.
101. Svetlizky, D.; Das, M.; Zheng, B.; et al. Directed Energy Deposition (DED) Additive Manufacturing: Physical Characteristics, Defects, Challenges and Applications. *Mater. Today* **2021**, *49*, 271–295. https://doi.org/10.1016/j.mattod.2021.03.020.
102. Ivántabernero; Paskual, A.; Álvarez, P.; et al. Study on Arc Welding Processes for High Deposition Rate Additive Manufacturing. *Procedia CIRP* **2018**, *68*, 358–362. https://doi.org/10.1016/j.procir.2017.12.095.
103. Ehmsen, S.; Conrads, J.; Klar, M.; et al. Environmental Impact of Powder Production for Additive Manufacturing : Carbon Footprint and Cumulative Energy Demand of Gas Atomization. *J. Manuf. Syst.* **2025**, *82*, 13–25.
104. Ehmsen, S.; Yi, L.; Glatt, M.; et al. Evaluating the Environmental Impact of High-Speed Laser Directed Energy Deposition: A Life Cycle Assessment. *Procedia CIRP* **2023**, *120*, 1606–1611. https://doi.org/10.1016/j.procir.2023.12.003.
105. van Sice, C.; Faludi, J. Comparing Environmental Impacts of Metal Additive Manufacturing to Conventional Manufacturing. *Proc. Des. Soc.* **2021**, *1*, 671–680. https://doi.org/10.1017/pds.2021.67.
106. Gutowski, T.; Jiang, S.; Cooper, D.; et al. Note on the Rate and Energy Efficiency Limits for Additive Manufacturing. *J. Ind. Ecol.* **2017**, *21*, S69–S79. https://doi.org/10.1111/jiec.12664.