



Technological capabilities and sustainability aspects of metal additive manufacturing

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Received: 30 May 2023 / Accepted: 24 October 2023 / Published online: 28 November 2023
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Abstract

Additive manufacturing technologies can produce complex components in a more efficient and environmentally sustainable way when compared with conventional manufacturing technologies. These advantages are expected to keep cementing Additive manufacturing role in several industries. *Additive manufacturing* technologies are fast-improving technologies with an estimated doubling of performance on average every five years. These fast developments make it difficult to keep track of current technological capabilities and environmental impacts. Among the most relevant *additive manufacturing* technologies there are the metal additive technologies of Powder Bed Fusion, Directed Energy Deposition and Binder Jetting. This paper assesses the current technological capabilities and environmental impact of *these* technologies. For that, resorting to data from literature, technical reports and company data sheets, the technological steps are defined, the relevant process parameters are established, and qualitative and quantitative data is gathered. A set of visualizations of process capabilities and their environmental impact is performed with the intent of helping designers and engineers with decision-making. It is also interesting for the research community to visualize and understand the current capabilities and to establish roadmaps for research. Limitations of this study include data currently available for each parameter, and the shortage of data for the environmental calculations.

Keywords Metal additive manufacturing · Technological capability · Performance improvement rates · Selection parameters

Abbreviations

AM Additive manufacturing
MAM Metal additive manufacturing

SLM Selective laser melting
EBM Electron beam melting
PBF Powder bed fusion
DED Directed energy deposition
BJT Binder jetting
L-PBF Laser powder bed fusion
WAAM Wire arc additive manufacturing
WLAM Wire feed laser-based additive manufacturing
EBF3 Electron beam freeform fabrication
EI Environmental impact
LCA Life cycle assessment
pt Points
SEC Specific energy consumption

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1 Introduction

Additive manufacturing (AM) technologies have had exponential growth in the last decade, with great developments in terms of equipment, productivity, and equivalent investment in research [1, 2]. In fact, the AM market has grown about 18.3% in 2022 [3].

Additive manufacturing has the potential to provide significant advantages, such as the generation of less waste during production; the possibility of unifying several functionalities in a single part, the ability to customize parts to a particular function [4] and the optimization of geometries creating lighter components and a subsequent reduction in transport and energy use [5]. AM processes can produce 3D parts with near-net-shaped dimensions layer-by-layer directly from 3D computer-aided design data [6, 7].

When evaluating AM as a production method, there is a strong interconnection between the process and the design [8]. The design process has gained increased flexibility due to the inherent characteristic of AM to offer greater geometric freedom compared to traditional manufacturing, albeit subject to specific limitations inherent to each metal additive manufacturing (MAM) [9]. For this reason, it is difficult to design a part that fully utilizes the AM's potential without understanding the flexibility and limitations that the technologies offer. As in any new technology, a key factor is knowing what the possibilities and characteristics are in terms of design, materials, process, and supply chain contexts. Furthermore, additive manufacturing technologies foster more sustainable production practices through lightweight parts, toolless operation, near or closer to 1:1 material usage ratio, flexible logistics and transport reduction [10, 11]. Therefore, economic, and environmental aspects are of paramount importance for the decision regarding the adoption of a specific AM technology for a part. The need to have early design indicators for these aspects, regarding both economic and environmental sustainability, is crucial in any technology or material selection process [12], especially in the case of AM [13].

In this work, the focus is on metal additive manufacturing, the second most used family of materials in additive manufacturing after polymers [14], of particular interest for the aerospace, medicine and other fields in which material savings and performance are critical, with the potential to produce high-value, customized products [13]. The widespread literature focused on recent developments, together with the constant evolution of equipment and standards makes the decision to adopt one or integrate

this knowledge in Design for AM particularly difficult. This paper contributes to the state of the art in the field of metal additive manufacturing (MAM) by defining key parameters for each technology, offering essential project constraints for the initial design phase of components. As well it maps current values for these parameters through an extensive review of literature and supplier data sheets. This allows for a preliminary selection of the most appropriate technology to produce a part taking into consideration technical, economic, and environmental aspects.

This paper is divided into five sections. After introduction, Sect. 2 revises the main MAM technologies, namely powder bed fusion (PBF), directed energy deposition (DED), and binder jetting (BJT). Section 3 focuses on the methodology used in this paper to collect and treat data. Section 3 addresses the identification, structuring and description of relevant parameters followed by data collection and analysis. Section 4 presents the results in the form of visualizations of the mentioned parameters for each of the MAM technologies. Section 5 draws the conclusions and discusses open points for future work.

2 Metal additive manufacturing technologies

Metal additive manufacturing technologies, according to ISO/ASTM 52900:2021 [15], are divided into five families: BJT, DED, PBF, material jetting, and sheet lamination. Due to the constant development of new equipment and new ideas around AM, there are other processes that are difficult to categorize due to their newness (e.g., selective powder deposition) [16]. This article focused on the three most used and established MAM technologies i.e. *PBF*, *BJT*, and *DED*.

2.1 Powder bed fusion

PBF is the most used metal additive manufacturing technology in aerospace and biomedical industries [17]. *PBF* resorts to either laser or electron beam as the power sources to fuse the metal powders in a bed layer-by-layer. An example of a process using a laser as a power source is Laser Powder Bed Fusion (L-PBF), and the process, using an electron beam is denominated Electron Beam Melting (EBM). Despite the efforts from ASTM and ISO [15], trademarks made their way to the imagination of researchers and scientists since each company assigned their trademarks to what their machines actually do and work. Other trademarks include DMLS™ for direct metal laser solidification or DMLM™

for direct metal laser melting, a melt pool is formed and a fully-dense structure, equivalent to wrought. Although very similar, the difference is that sintered-based manufacturing uses less energy and does not require full melting of the powder, it also allows the use of mixtures. There are also PBF of polymers, but they are out of the scope and for further reading, consider Schmid et al. [18].

All these processes are similar since they belong to the same family, where a thin layer of powder is deposited over a substrate plate or on the previously deposited layer and subsequently melted or sintered selectively by a laser or a beam of electrons, as dictated by the *CAD* data [19–21]. Several process factors influence the quality of the final component, thus, requiring to be adjusted to ensure a low number of defects, such as lack of fusion or gas pores [22–24].

Some of the important process variables are laser/beam power, scan speed and scan strategies which can have a significant effect on the mechanical properties of the final components [25, 26]. The manufacturing process takes place inside an enclosed chamber, usually filled with an inert gas in *SLM* and in a vacuum in the *EBM* process. The chamber allows for controlled processing temperature which is directly correlated with the final characteristics of the components. In *SLM* systems, substrate plate heating is generally applied to reduce the cooling rate and thermal gradients, thus preventing solidification cracks and reducing residual stresses [27]. Compared to *SLM*, the *EBM* process is more suitable to process materials more susceptible to hot cracks since it allows reaching higher processing temperature through preliminary heating scans [28, 29].

Production rates and costs are two highly relevant characteristics of manufacturing technology. While machine speed variations can be substantial, overall, powder bed fusion (PBF) typically exhibits lower processing speeds compared to DED and BJT systems. However, multiple laser sources can be installed to increase build rates [30]. In terms of costs, studies have shown that the powders can theoretically be reused repeatedly [31–33]. This reduces the wastage of raw materials and the overall production cost. However, standards such as the AMS7031 in the aeronautical sector define handling procedures and properties of metal powder feedstock to be reused [34].

2.2 Binder jetting

BJT is carried out by depositing droplets of binder on the powder layer by means of a printing head. It is a well-known process, but it has been mainly used with sand and ceramic materials [35, 36].

BJT involves several post-processes that follow the printing of parts, such as curing, depowdering, debinding, sintering, infiltration, annealing, and finishing [37]. The curing process can be done by heating the green part so that the binder hardens and facilitates handling. Depowdering consists of the removal of the printed piece from the powder bed. The part is then debinded and sintered. These steps are essential to achieve a solid part with high mechanical properties. Metal infiltration can be performed to enhance part density. Other heat treatments can be performed to dissolve unwanted second phases (solution treatment) or to promote hardening by the precipitation of intermetallics or carbides.

Such post-process treatments (especially debinding and sintering) can take longer than the printing phase and may lead to high costs [38]. BJT generally does not require support structures, offering a significant advantage by enabling the production of highly complex parts. However, it is important to note that support structures may still be necessary during the sintering stage, which can influence the overall geometric complexity. Moreover, the entire build volume can be closely packed with several stacked parts [39].

BJT is compatible with a wide range of materials, even those that are sensitive to hot cracks and can barely be processed by DED and PBF technologies. [40]. The printing process occurs at a controlled room temperature, avoiding problems related to oxidation, residual stresses and powder reuse [38].

In BJT the consolidation takes place predominantly by sintering, printed parts are commonly characterized by a higher amount of defects compared to DED and L-PBF parts [41]. Finally, the design should carefully take into consideration the anisotropic contraction of parts during debinding and sintering [42].

2.3 Directed energy deposition

DED processes are classified into powder and wire types according to the fed material [43–45]. The volume density of the fabricated part by DED processes is nearly 100% [45]. Due to the local melting and rapid cooling, the resultant microstructure consists of well-refined grains, and parts built by this process usually exhibit 30% higher strength than those built by casting [44]. This process is suitable for part repair [46], as the damaged portions can be restored selectively. Another advantage of this process is its ability to add coatings (or clad) to existing surfaces [47, 48].

It is a form of automated build-up welding. The deposition principle of the powder-DED is based on the laser cladding process [49, 50]. The melted region is created by

the laser on the substrate and the previously deposited layer. Subsequently, metallic powders are supplied to the melted region. At the same time, the supplied powders are melted by the heat of the melted region and the laser. The powder-DED employs the laser head with powder-feeding nozzles [50]. The head allows the deposition of new metallic layers while the laser fuses the layer [49], making the process suitable for repairing and remanufacturing parts [45, 51]. Moreover, powder-DED can be carried out using multiple materials, providing a key solution to fabricate heterogeneous material parts, including different functionalities [45, 49].

Three categories of the wire-DED process, including wire arc additive manufacturing (WAAMTM), wire feed laser-based additive manufacturing (WLAM), and electron beam freeform fabrication (EBF³) processes, have been developed. The dimensional accuracy and the surface roughness of wire-DED are inferior than those of the powder-DED process, whereas the build rate of the wire process is significantly superior than that of the powder process [44, 45].

2.4 Relevant parameters in metal additive technologies

MAM technologies have constantly been developing and improving their technological capability in recent years. Each metal additive technologies have its particularities and can produce materials and composites with different characteristics. A comparative analysis between MAM technologies is necessary to help in decision-making. Depending on the competitive factors that are given priority in the manufacturing system under investigation, AM technology may be acceptable or inappropriate. The many elements of additive manufacturing technologies, along with the absence of standards and the organizations' lack of expertise, make choosing an AM technology challenging [52].

It is necessary to understand which parameters are important to assess the technical capability to choose a certain additive manufacturing technology. Few studies were found in the literature on AM technology selection for the production of parts. Gokuldoss et al. [53] discuss the different selection criteria based on the analysis of the different energy sources used in the AM. With a defined set of

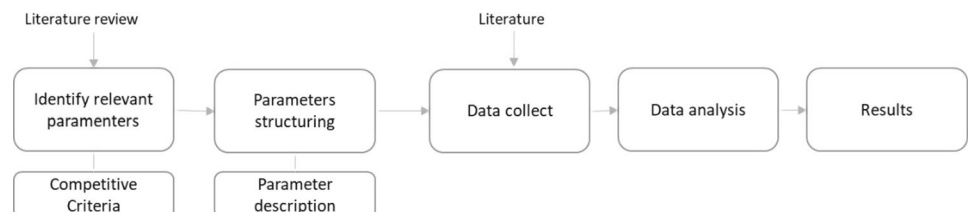
material properties, they suggest seven selection criteria which are: (i) type of material to be processed, (ii) technology availability, (iii) properties and service requirements of parts, (iv) type of application, (v) post-processing requirements, (vi) surface quality, and (vii) accuracy. Another criterion proposed for the selection of the most ecological manufacturing, according to Priarone and Ingarao [54], was the environmental impact of different additive processes in comparison with conventional subtractive manufacturing processes.

A decision-making proposal for MAM was developed by Calderaro et al. [55] and it is based on the characteristics of additive technologies and competitive criteria for the selection of additive manufacturing technologies in production systems. They proposed four competitive criteria for the analysis, i.e. velocity, flexibility, quality, and cost.

Within the decision analysis literature, there has long been an understanding that the use of quantitative modelling should be assessed largely by the quality of the results. Manufacturing limitations, product characteristics, and customer needs are only a few of the important factors utilized in the selection process to discover the best option for a part, component, or product [56]. The general challenge in the construction of selection tools for specific manufacturing consists in systematically identifying the correspondence between the design requirements and the capabilities of the process [57], in line with the Ashby approach [58], to interrelate design, material, and process. Shercliff and Lovatt suggested three groups to help identify requirements [57]. The design-related are the specifications for the function of the component; the production-related are the details required for the factory floor; and the processing-related are the process problems that can be eliminated in the planning and production stage. The requirements can then be grouped into four types, i.e. technical feasibility, absence of process defects, product performance, and economics.

The metal additive technologies have several parameters that represent the characteristics of their processes, however, in the literature there are still few studies about decision-making and surveys of the relevant parameters for the analysis of technological capability. Furthermore, sustainability criteria are generally left out of these approaches.

Fig. 1 Methodology to assess the capability of additive technologies



3 Methodology

An overview of the methodology used in this work for obtaining the technological capability is shown in Fig. 1. The first phase of the methodology is focused on understanding MAM technologies and on the identification of necessary steps for each of the investigated manufacturing processes by a systematic literature review. Scientific articles and specialized journals on additive technology equipment, books, and standards were reviewed to understand the particularities of each technology/process and their key parameters.

Following the general understanding of each process, process information is collected and filtered for relevant parameters. These parameters are used to facilitate the understanding of the manufacturing processes and have the potential to characterize technologies.

Some parameters are directly related to the behaviour of the product in service and are significant to the decision-making, while others are process parameters and are irrelevant to the selection. For example, layer thickness directly impacts surface roughness, build time and overall costs, whereas setup time, although is an important cost driver is only relevant for selection in this model if material changes often occur.

Based on the model suggested by Calderaro et al. [55], the relevant parameters were established, following the competitive criteria and through the Analytic Hierarchy Process (AHP) methodology. Paired analyses of additive technologies were conducted for each competitive criterion.

After parameters identification, this study focussed on the classification of the competitive criteria for comparative analysis of technological capability proposed by Calderaro et al. As mentioned above, according to this study, the competitive criteria are grouped into four categories: cost, flexibility, speed, and quality.

In this work, to include the perspective of sustainability, environmental impact is also analysed as an additional competitiveness criterion.

After structuring the parameters, data were collected. Literature data are further reviewed to collect values corresponding to each relevant parameter selected. The data is then organized in the form of maximums and minimums, which will depend on what represents the best scenario for the parameter under analysis.

3.1 Relevant parameters

In this work, the relevant parameters are those that demonstrate an important characteristic of technology capability.

Table 1 Shows the literature parameters and the type of collecting the data

Parameters	Type	References
Energy source	qualitative	[3, 60, 61]
Process time	Quantitative	[3, 40, 62]
Process steps	Qualitative	[63–65]
Manufacturing time	Quantitative	[66–68]
Raw material	Qualitative	[69–74]
Layer thickness	Quantitative	[40, 75–78]
Density	Quantitative	[79–83]
Detail resolution	Quantitative	[84–90]
Dimensional accuracy	Quantitative	[84–93]
Surface quality	Quantitative	[94–97]
Multi-material capability	Qualitative	[63, 98–102]
Build volume	Quantitative	[103–105]
Geometric limitations	Qualitative	[40, 64, 106–110]
Environmental Impact Cost per unit of volume	Quantitative quantitative	[104, 105, 111–116] [63, 117, 118]

From the statistical perspective, a parameter implies a summary description of the characteristics of an entire population based on all the elements within it [59].

With a first review of the literature, 15 main parameters were defined for the investigated technologies (see Table 1).

It is possible to correlate which competitive criteria are directly linked to the mechanical and physical properties of parts. Parameters that represent features that are already described by other parameters have been discarded. Layer thickness and process steps parameters are indirectly covered by another parameter, i.e. process time. The parameters that are not relevant were also discarded. These parameters demonstrate characteristics that are not able to define the technological capability or crucial for decision making, for example, energy source and material source.

Thus, only thirteen out of the initial fifteen parameters are considered for the present study, and each of them is classified within the competitive criteria. All selected parameters can characterize the capability of the technologies following some competitive criteria (see Table 2).

3.2 Parameters structuring

Competitive criteria can be conceptualized as the factors evaluated by customers at the time of the purchase decision [119]. In terms of comparative analysis between technologies, the competitive criteria are a way of comparing technologies for decision-making at the organization's strategy level. Strategic high-level considerations

Table 2 Parameters to evaluate technological capabilities

Competitive Criteria	Characteristics of AM Technology	Capability evaluation parameters of AM Technology	Nomenclature	Parameters Type	
Speed	Manufacturing time	Machine's build rate	Build rate	Quantitative	
	Total process time	Process time of all manufacturing steps	Process time	Qualitative	
Flexibility	Geometric limitations	Wall thickness	Wall thickness	Quantitative	
		Unsupported walls	Unsupported walls	Quantitative	
		Embossed/engraved details	Embossed/engraved details	Quantitative	
		Unsupported edges	Unsupported edges	Quantitative	
		Fillets	Fillets	Quantitative	
		Hole size	Hole size	Quantitative	
		Escape holes	Escape holes	Quantitative	
		Feature Size	Feature Size	Quantitative	
		Manufacturing Dimensions	Machine's build volume	Build volume	Quantitative
		Raw material	Metal alloys	Raw material	Qualitative
Quality	Multi-material	Multi-material feature	Multi-material	Qualitative	
	Surface quality	Surface Finish (Ra)	Surface Finish	Quantitative	
	Precision	Layer Thickness	Layer Thickness	Quantitative	
		Machine's dimensional accuracy	Minimum dimensional accuracy	Quantitative	
		Machine's dimensional detail	Minimum detail resolution	Quantitative	
		Mechanical Properties	Component's density	Density	Quantitative
Cost	Manufacturing Cost	Energy Consumption	Cost per unit of volume	Quantitative	
		Machine's acquisition cost			
		Material cost			
Sustainability	Environmental Impact (EI)	EI raw material	EI	Quantitative	
		EI energy consumed in printing		Quantitative	

of machine portfolio management, client-based decisions, and access to external funding are out of the scope of the current work.

The cost is an important criterion due to the high initial investment in MAM technologies and material cost [55].

Regarding competitive flexibility, some publications highlight this characteristic of additive manufacturing as one of the benefits compared with the conventional method of production [120]. To analyse the technological capability, it is necessary to understand the parameters of Design for AM that differentiate these technologies from traditional manufacturing.

Regarding the competitive speed criteria, the use of AM technologies alters how companies operate, such as aspects of production, caused by the ability of AM technologies to produce on-demand and profitable parts [121], supply chain, maintenance, and product development [122]. When analysing this criterion between the different AM technologies, each step of the process is accounted to have a global analysis of the production time, including the different needs

of post-processing. For example, the binder jetting process time has to account not only for deposition time, but also for sintering time, and that encompasses stacking several parts for the oven at the same time.

The capacity of a component to perform its function effectively may be regarded as meeting the quality competitive criteria and being crucial for gaining a competitive advantage.

The sustainability criterion suggested here refers to the ability of additive manufacturing (AM) to minimize the need for resource and energy-intensive manufacturing processes, which in turn lowers the quantity of material needed in the supply chain and makes it possible for more environmentally friendly practices, which was shown as very promising [123]. Being an extremely important criterion, especially in the current scenario, with the need for more sustainable manufacturing processes.

Table 2 shows each of the relevant parameters selected in Sect. 3.1 and their organization distributed among the competitive criteria.

There are high-level technological selection criteria established in the literature [55] that are based on the dimension of technological competitiveness. Allocated to these competitiveness criteria are characteristics of the technology (see column 2). These characteristics of the technology can be translated into measurable parameters qualitatively and quantitatively (see column 3).

3.2.1 Parameters description

A succinct description of each parameter offered in Table 2 is reported in this section. The purpose of this description is to generate an equalized understanding of the decision-making process and a basis for data gathering, prioritization, and selection.

Build rate rate of consolidated powder volume per unit time, i.e., the speed of construction, including the deposition of powder and the consolidation of parts by means of the binder, laser, or electron beam. It is a parameter that clearly demonstrates the speed of the printing phase production.

Process time the time of the process impacts the entire production process and management of a business; therefore, it is a selection criterion for the choice of technology considering all the time of the pre-processing, manufacturing, and post-processing processes of the part. The processing time is closely linked to the build rate of the process and can be used to evaluate the time efficiency of AM technologies. The deposition rate defines the ratio between the total mass melted and the total time required to produce a part. A study carried out by Lunetto et al. [124] shows that the presence of lattice structures and supports delay deposition efficiency and that parts composed mainly of molten volumes have the highest deposition efficiency. The process time in additive manufacturing can be influenced by the height of the part. This is because the properties of the bulk material, such as particle size and viscosity, can affect the way the material is deposited during the printing process. Additionally, the dispersion of fine particles, including the time it takes for dust scattering, which is a non-active phase, to settle, plays a role in the deposition process. When the height of the part is increased, there is a greater vertical distance for particles to travel, potentially leading to more dust scattering and longer settling times during the non-active phase. This, in turn, can impact the overall process time.

Building volume the size of the part is limited by the printing area of the machine; this selection criterion allows us to determine which technologies can manufacture the part with its dimension established in the technical requirements.

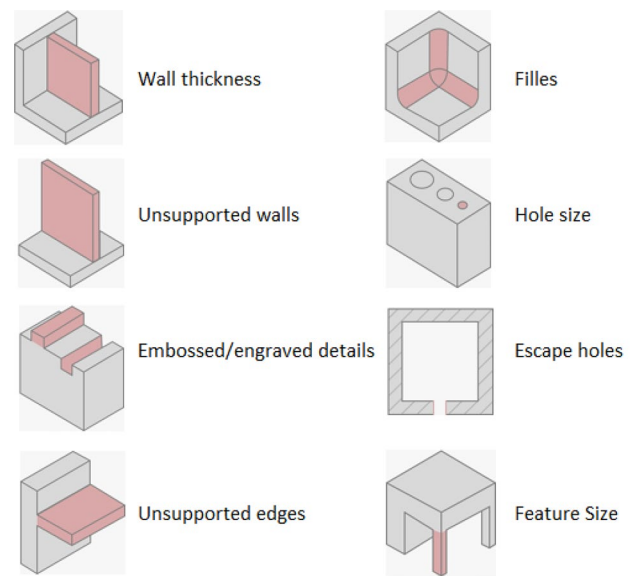


Fig. 2 Parameters to geometric limitations. Source: Based on Redwood et al. [107]

Raw material material is extremely important to establish the technical requirements, and in addition, the raw material selection criterion defines which technologies allow for a part to be manufactured with a certain material, as the technologies have limitations as to the materials capable of being manufactured by AM.

Multi-material the ability to manufacture multi-materials is an advantage that some equipment has; this criterion is basic when it comes to composite materials and parts/systems composed of different metals. Therefore, it is necessary to select which technologies are suitable for the manufacture of multi-materials in the AM to meet the technical requirements of the project.

Geometric limitations the limitations can be from process characteristics that make some geometries unfeasible. In design considerations, wall thickness can be a limitation, as well as minimum hole diameter, layer thickness or internal structures. Figure 2 shows the description of each parameter analyzed to demonstrate the geometric limitations according to the design for AM.

Surface finish (R_a) R_a is the surface roughness of the final component; technologies have different final roughness in their processes depending on the parameters used during manufacture, namely: laser power, the deposition rate of the raw material, working temperature, layer thickness, type binder, among others.

Table 3 Definitions and relation of competitive criteria with certain parameters of MAT

Competitive Criteria	Definition	Parameters of AM	Relationship
Cost	The cost for manufacturing	Calculate €/cm ³	The smaller the better
Flexibility	The technology's capacity to adapt its products to customer needs	Wall thickness Unsupported walls Embossed/engraved details Unsupported edges Filletts Hole size Escape holes Feature Size	The smaller the better
Quality	Provide low-defect products that are manufactured in accordance with defined criteria	Build volume Raw material Multi-material Surface finish Minimum dimensional accuracy Minimum detail resolution Layer thickness	The bigger the better
Speed	The technology's capacity to produce items in the quickest amount of time	Density Build rate Process time	The bigger the better The smaller the better
Environmental Impact	The technology's capacity to manufacturing items most ecological	Calculate EI (Pt)	The smaller the better

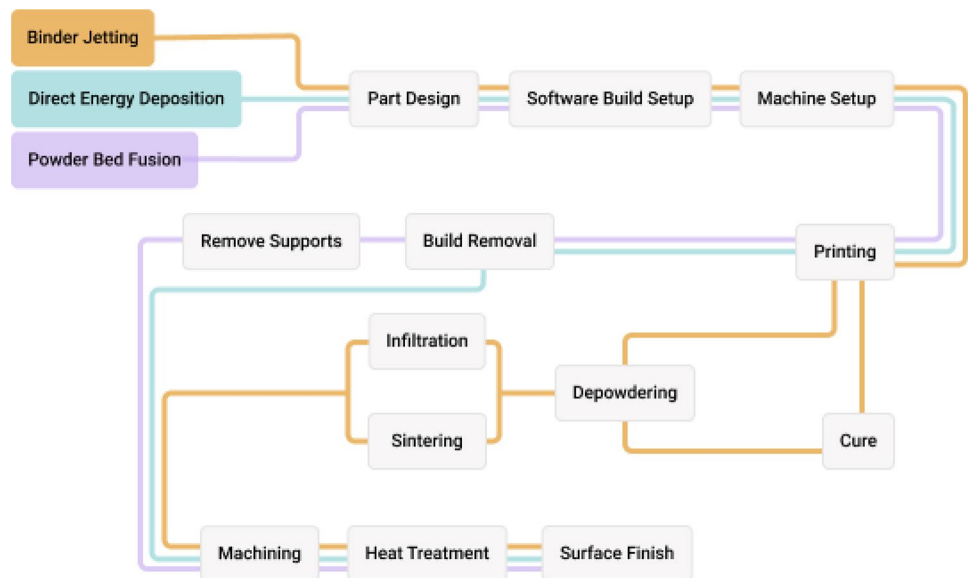
Source: based on Calderaro et al. (2020) [55]

Layer Thickness Layer thickness refers to the predefined thickness of individual metal layers deposited during 3D printing. It plays a vital role in determining the final quality and surface finish of the metal part. This parameter, measured in micrometers (µm) or millimeters (mm), can be adjusted based on the application's requirements. Smaller layer thicknesses yield finer details but longer printing times, while thicker layers expedite the process at the expense of

some detail and surface quality. Finding the right layer thickness is crucial for balancing production speed and part quality in metal additive manufacturing.

Minimum dimensional accuracy accuracy refers to how well the equipment can perform from what was planned in the software to the printing platform, that is, the ability to accurately produce the dimensions required in the original CAD file of the design. Components with low tolerances

Fig. 3 Process Steps in the Metal Additive Manufacturing



and complex design levels require very high manufacturing accuracy.

Minimum detail resolution detail resolution is the smallest feature size the technology can make, translated in terms of ratio scale [40].

Density density in additively made parts refers to the porosity of a part, it is a property that is directly influenced by the material, powder particle size, build chamber temperature, laser speed and temperature to be used, and the geometry of the part. Density is an important feature when choosing the technical requirements of the part, as it influences the mechanical properties of the part, especially its strength, and stiffness. This is particularly important if the parts must withstand fatigue or other types of loads.

Environmental Impact it is an indicator widely used to quantify environmental impacts, and therefore a selection criterion that allows analyzing the environmental impact of the processes. This criterion assesses the environmental impact caused by industrial input activities, focusing on the damage impact on ecosystem quality, resources, and human health through the normalization of data related to the product/process lifecycle into a single unit called pt (points).

Cost per unit of volume the cost per cubic centimeter is the most used criterion for selecting production processes. It has high relevance for choosing the most appropriate additive technology. It is a criterion used in many studies that involve the selection of materials, processes, and technologies [125–127].

3.3 Data collection

Having the competitive criteria and the characteristics of the AM technology elicited, a comprehensive data collection can start. This is based on the analysis of state-of-the-art technology. There are several sources of information available to collect and selection of raw data for this paper. Data sources include catalogues from equipment manufacturers, product specifications, benchmarking, trade magazines, scientific literature, and industry reports [125].

In this study, the main approach for data selection was product specifications and industry reports. The product specifications (technical sheets) that are often released along with the announcement of a new product or technology and industry reports are documents compiled on the state of an industry by either private firms or sometimes government agencies.

The survey of state-of-the-art technology data and the initial selection of manufacturing companies were based on

Wohler's report [3]. To get a reliable understanding of technology, it is important to get as many data points as possible. The number of companies analyzed was complemented with research in the literature and on AM machines sites. In total, data from 329 machines distributed among the MAM were analyzed.

The companies under analysis are not the only ones to produce AM for metals; however, they are the ones that provided a greater amount of information about all the criteria, being possible to have a greater perception of the technological capability.

3.4 Data analysis

Data analysis uses the parameters established in Sect. 3.2 and consists of organizing the data in the most appropriate way according to the nature of the data, namely: ranges of values, maximum and minimum, and averages. Table 3 shows the comparative relationships for evaluating the parameters.

In the first phase of the analysis, the parameters density, surface finish, raw material, detail capacity, dimensional accuracy, build volume, build rate, geometric limitation, and multi-material capability were taken from the literature and organized in the table in Annex V.

The second phase of the selection criteria analysis refers to the process time, environmental impact, and unit cost which are described below.

3.4.1 Process time

The additive process to manufacture metallic parts is, in general, based on the union of the material through an energy base that can be an electron beam, laser, or adhesive liquid. This metallic material is always built in layers and can be added as a powder or as a wire. Although they produce metallic parts, the processes for metals are different regarding the production steps (see Fig. 3), and this needs to be considered for decision-making, as each step has costs and requires different production times [55], in addition to the environmental impacts they have on the environment.

The comparative process time of the additive technologies contains all the steps necessary for the manufacture of the part and is shown in Fig. 3. For each phase of the process, the particularities of each technology that can impact the process time are analysed.

<p>Part Design</p> <p>Binder Jetting</p> <p>Direct Energy Deposition</p> <p>Powder Bed Fusion</p>	<p>The part design is the stage of construction of the project in 3D through software. The time for design parts, in general, is very similar for the three technologies. However, for PBF and BJT, it is still necessary to include the evaluation and implementation time of the necessary supports.</p>
<p>Software Build Setup</p> <p>Binder Jetting</p> <p>Direct Energy Deposition</p> <p>Powder Bed Fusion</p>	<p>This time is similar in all technologies, as there are no differences in this step of the process. The software build setup phase refers to the time to convert the part design into a machine-readable (STL) compatible file. The machine setup varies a lot according to the equipment.</p>
<p>Machine Setup</p> <p>Binder Jetting</p> <p>Direct Energy Deposition</p> <p>Powder Bed Fusion</p>	<ul style="list-style-type: none"> - The BJT requires an additional step, which is to take the building platform to the oven. - PBF needs inerting building chamber (laser beam source) or a vacuum atmosphere (electron beam source) - PBF preparation as additional steps compared to BJT and DED.
<p>Printing</p> <p>Binder Jetting</p> <p>Direct Energy Deposition</p> <p>Powder Bed Fusion</p>	<ul style="list-style-type: none"> - DED usually has the highest build rate, due to the relatively fast material deposition capability. - BJT with a high build rate through the binder fluid. - PBF with a lower build rate and requires the inclusion of supports to ensure that there is no deformation in the part structure due to temperature differences during the process.
<p>Cure</p> <p>Binder Jetting</p>	<p>The curing involves solidifying the binder and ensuring that the component achieves sufficient mechanical strength to allow for handling during subsequent processes.</p>
<p>Depowdering</p> <p>Binder Jetting</p>	<ul style="list-style-type: none"> - In BJT, it is necessary to remove the free powder not affected by the binder, which is scattered around the green part. (depowdering). - After curing and depowdering, the relative density of the green part is typically in the range of 50% to 60%.
<p>Sintering</p> <p>Binder Jetting</p>	<ul style="list-style-type: none"> - The time will depend on the material used and the dimension of the part, but usually the sintering time is significant. - Gravity influences slumping during the sintering process; hence the part's orientation must be considered.
<p>Infiltration</p> <p>Binder Jetting</p>	<p>If one further densification is needed to obtain the desired density and target mechanical properties, infiltration is then used to decrease the porosity of the part and this step can be included in the BJT process depending on the design requirements.</p>
<p>Build Removal</p> <p>Direct Energy Deposition</p> <p>Powder Bed Fusion</p>	<p>The build removal is the removal of the component from the machine's printing chamber. When it comes to DED this step is just removing the component. May involve removing the platform.</p>
<p>Remove Supports</p> <p>Powder Bed Fusion</p>	<p>The removal of the supports occurs in the PBF process and BJT, and the number of supports will depend on the project design and choice of part orientation. This time is relevant due the delicate process.</p>
<p>Machining</p> <p>Binder Jetting</p> <p>Direct Energy Deposition</p> <p>Powder Bed Fusion</p>	<ul style="list-style-type: none"> - The amount of machining required depends on the complexity of the part, the number of holes, and the dimensional accuracy. - BJT process has a shrinkage factor from the sintering step, but the process can produce parts with dimensional accuracy as good as PBF. - DED may need more machining time to make dimensional adjustments on the part due to the lower-dimensional accuracy.
<p>Heat Treatment</p> <p>Binder Jetting</p> <p>Direct Energy Deposition</p> <p>Powder Bed Fusion</p>	<p>The heat treatment is used to improve the mechanical properties of the part, so it depends much more on the type of material used and the size of the part than on the technology used. DED and PBF often required a stress relaxation heat treatment, which is not required by BJT.</p>
<p>Surface Finish</p> <p>Binder Jetting</p> <p>Direct Energy Deposition</p> <p>Powder Bed Fusion</p>	<p>In processes such as BJT and PBF, the part roughness is lower compared to DED. The lower roughness value is due to the higher level of precision of the PBF and BJT processes, as well as the higher build rates of DED can produce a rougher surface finish.</p>

Table 4 Materials used for the Life Cycle Assessment (LCA) analysis

Type of resource	Classification	Specification	Unit
Materials	Stainless Steel	316L	kg
	Steel alloys	SS 17–4 PH	kg
	Titanium alloys	Ti6Al4V	kg
	Aluminium Alloys	AlSi10Mg	kg

3.4.2 Environmental impact (pt/kg)

The evaluation of the environmental aspects and potential impacts associated with the utilization of the technologies was developed following the Life Cycle Assessment (LCA) methodology. The LCA was established by UNEP/SETAC, and the standardized format of the LCA framework was defined by the ISO14040 standard [128]. Although there

are other methodologies for analyzing the environmental impact, LCA has been the most used [129] and accepted for both academic and industrial objectives [130].

This life cycle methodology allows the evaluation of the environmental performance of the processes in the different scopes, from the cradle-to-grave, as well as evaluating only from the cradle-to-gate [131]. In the context of this study, the cradle-to-gate scope was adopted, that is, simply examining the extraction, and transformation of the raw material, the manufacturing phases and the power consumption of the AM process. The analyses did not consider the impact of shielding gas consumption on the environmental analysis due to a lack of reliable available data.

The set of resources to be considered in this analysis regarding the PBF, BJT and DED printing phase comprise the powder feedstock material and the source of the electricity generation with resources and emissions taken from

Table 5 Parameters of BJT technology [106]

Binder Jetting		
Parameters	Recommended minimum value	Observations
Wall thickness	2 mm	Minimum to reduce damage in the removal and handling process
Unsupported walls	3 mm	To reduce the risk of damage during handling
Embossed/engraved details	0.5 mm	Minimum below or above the surface for visible requirements
Unsupported edges	2 mm	Minimum to avoid breaking in the green state
Fillets	1 mm	Minimum to avoid damage in the green state
Hole size	1.5 mm	Minimum diameter
Escape holes	5 mm θ and 2 escape holes	Minimum in hollow sections to remove the unbound powder after printing
Feature Size	2 mm	Minimum to very fine details, leave the most brittle parts in the green state

Table 6 Specifications of PBF technology [107]

Powder Bed Fusion		
Parameters	Recommended minimum value	Observations
Wall thickness	0.4 mm	Minimum depending on material, orientation and printer parameters
Unsupported walls	0°–30°	Need supports
	30°–45°	Supports not needed, part may have poor surface on down facing surfaces
	> 45°	Supports not needed, good quality surface finish
Embossed/engraved details	0.5 mm	Maximum length of a cantilever-style overhanging surface
	1 mm	Overhanging horizontal surface supported on both ends
Unsupported edges	0.5 mm	Maximum length of a cantilever-style overhanging surface
	1 mm	Overhanging horizontal surface supported on both ends
Fillets	1 mm	Add fillets to decrease stresses at geometry changes
Hole size	0.5–6 mm	Supports not needed
	6–10 mm	Supports not needed orientation dependent
	> 10 mm	Need supports
Escape holes	2 mm	Minimum value, multiple or larger holes will increase the speed of powder removal
Feature Size	0.8 mm and maximum height: width ratio of 8:1	Features with greater aspect ratios risk damage by the recoater during powder application

Table 7 Specifications of DED technology [108–110]

Direct energy deposition		
Parameters	Recommended minimum value	Observations
Wall thickness	0.25 mm	5–15 times of wire diameter [108]
Inclined thin walls	2.5 mm when $\beta=60^\circ$	The minimum wall width is the layer width
Unsupported walls	Maximum angle of $30^\circ\text{--}35^\circ$	From vertical using 2.5D slicing (ability to use multi-axis slicing Removes this limitation) [109]. The width of the overhang should not be larger than the wall width to minimize the thermal influence on the manufactured wall [110]
Curved walls	Radius = 2.5 mm	Curved elements perpendicular to the building direction should have a minimum radius to reduce the angular shift between the layers
Embossed/engraved details	Not applicable	–
Unsupported edges	Depends on the number of machine axis	–
Fillets	Not applicable	–
Hole size	Wire diameter	Holes And channels normal to the build direction need to be Modified to tear drop, lemon shaped, diamond shaped or by Adding angled support into the design [108]
Escape holes	Not applicable	–
Feature Size	Bend-like features	Made possible by utilizing the tilt/rotate table in incremental steps [109]

the Ecoinvent 3.7 database representing global averages. The environmental impact is quantified and later analyzed into different impact categories using the ReCiPe2016 method [132] in SimaPro software.

Initially, the ReCiPe Endpoint (H) V1.11 / World Recipe H/H method is used to convert and evaluate the list of life cycle inventory using endpoint indicators among the selected environmental effect into three categories: human health, ecosystems, and resources.

This data allows a simplified analysis in a preliminary stage to be able to perceive the differences between the technologies. The endpoint characterization is easy to interpret in terms of the relevance of the environmental flows [132]. The environmental impact of manufacturing a component per kg of material ($EI_{component_{AM}^{mat}}$), using this impact method, is given by pt/kg.

Table 4 shows the materials used for the LCA analysis. The materials using the database, and the individual inventories for the creation of each material can be found in Annex II. The main environmental drivers, material, and energy were considered in both processes for this simplified analysis.

The values were all based on the ones obtained in database machines, and the remaining values were obtained from a previous study on the energy requirements of manufacturing processes (see Table 4).

The environmental impact of manufacturing a component per kg of a material is given by:

$$EI_{component_{AM}^{mat}} = EI_{mat} + EI_{manufacturing_{AM}^{mat}} \tag{1}$$

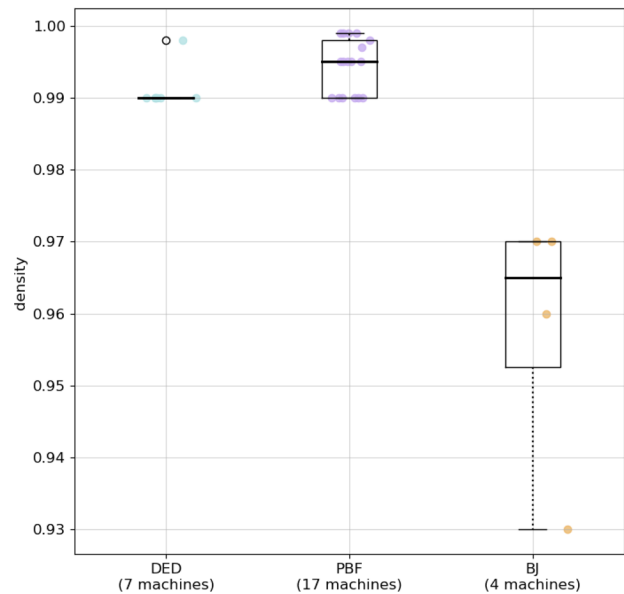


Fig. 4 Density according to metal additive technology

where EI_{mat} is the environmental impact of the raw material per kg and comes in pt/kg, and $EI_{manufacturing_{AM}^{mat}}$ is the environmental impact of manufacturing a component by AM per kg of material and comes in pt/kg.

$EI_{manufacturing_{AM}^{mat}}$ is calculated by correlating the build rate given in cm^3/h , that is, the volume of material built per unit of time, the density of the material (ρ) in kg/cm^3 , the machine power consumption given in kW, and the

Table 8 Density according to source energy

Technology	Energy source	Average density (%)
Direct Energy Deposition	Laser	99.4
	Electrom Beam	99
	WAAM	99
Binder Jetting	BJT	94.67
Powder Bed Fusion	Laser	99.53
	Electrom Beam	99.5

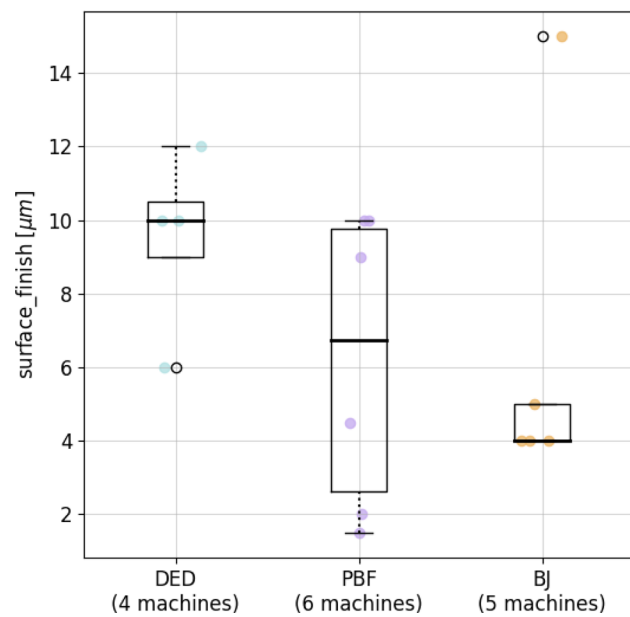


Fig. 5 Surface finish according to metal additive technology

environmental impact of the electricity generation (EI_{energy}) given in Mpt/kWh is calculated with the corresponding pt value of Portugal’s medium voltage electricity.

$$EI_{manufacturing_{AM}^{mat}} = \frac{1}{build.rate \left(\frac{cm^3}{h} \right) * \rho \left(\frac{kg}{cm^3} \right) * power.consumption(kW) * EI_{energy} \left(\frac{pt}{kWh} \right)}. \tag{2}$$

3.4.3 Cost per unit of volume (CUV)

The volumetric cost (€/cm³) is the manufacturing cost per cubic centimeter and comprises the material ($C_{material}$) and machine cost ($C_{machine}$). It’s important to notice that the manufacturing cost depends heavily on the chosen process/machine and its raw material. As an example, the aluminum

cost may differ if it is used as a powder (for PBF) or wire (for wire DED). Therefore, the volumetric cost is specific for each product, machine, and raw material combination.

$$C_{uAM}^{mat} = (C_{material} + C_{machine}). \tag{3}$$

The material ($C_{material}$) and machine cost ($C_{machine}$) is given in €/cm³. Machine cost is calculated by dividing the hourly cost ($M_{C/H}$) by the build rate (*build.rate*), given in cm³/h.

$$C_{machine} = \frac{M_{C/H}}{build.rate}. \tag{4}$$

The machine’s annual cost ($M_{annualcost}$) refers to the annualization of the acquisition of the machine (investment). The investment is dependent on the opportunity cost of capital, the machine’s lifetime, as well as to their usability as dedicated or non-dedicated equipment. In cases where the machine is dedicated, the hourly cost ($M_{C/H}$) is calculated by the annual cost of the machine ($M_{annualcost}$) and the uptime (t_u).

$$M_{C/H} = M_{annualcost} * t_u \tag{5}$$

For this comparative analysis, we consider a constant uptime independent of the machine selected.

4 Results

This section encompasses the results for each of the 11 characteristics of AM technologies described in Table 2. MAM technologies have different manufacturing processes, but in many cases, the parameters are the same and/or very close between them. The analysis of the design for AM allows an understanding of the metallic part manufacturing particularities, where all stages of the processes are considered and specificities of each additive technology. The macro view of this context is essential to understand the technological boundaries as well as their intersections.

4.1 Geometric limitations

Geometric limitations for each technology help the designer realize the thresholds of the technology. As shown in Tables 5, 6, and 7, the specifications are detailed in the observations, and the minimum values for each of them, which are: wall thickness, unsupported walls, embossed and engraved details, unsupported edges, fillets, hole size, escape holes, feature size, curved walls, and inclined walls. These values can be used as suggestive or approximate values.

Fig. 6 Raw material in additive manufacturing technologies

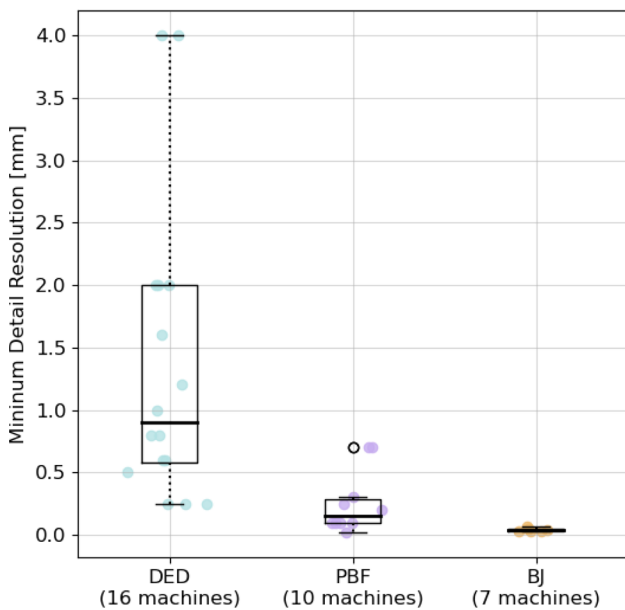
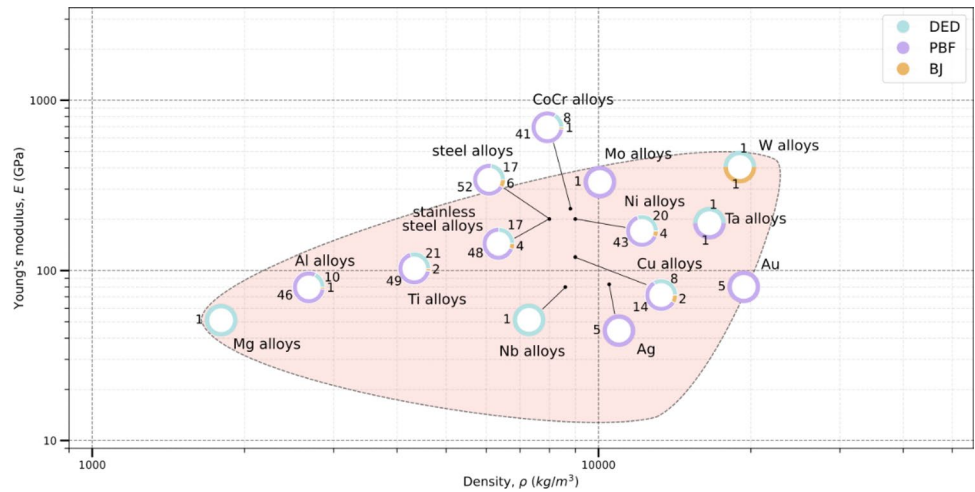


Fig. 7 Minimum detail resolution according to metal additive technology

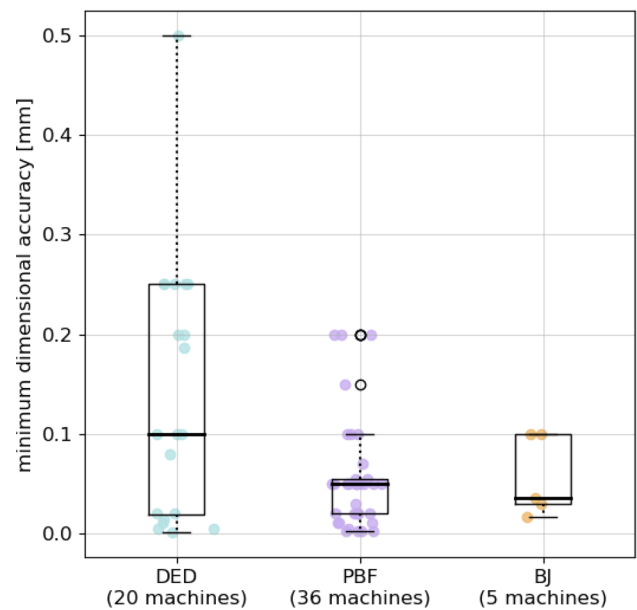


Fig. 8 Minimum dimensional accuracy according to metal additive technology

4.2 Density

The relative density of the three technologies is shown in Fig. 3, where binder jetting has a greater variation in density values depending on the equipment and with values lower than those of other technologies, with a smallest value of 0.93 g/cm³ and a higher value of 0.97 g/cm³. This is also influenced by the process of joining the layers, i.e., sintering/melting. Due to the sintering process of the binder jetting being carried out after the part is manufactured, residual pores are usually present in sintered parts, leading to lower density values compared to other technologies.

Table 9 Selection criteria according to metal additive technology

Technology	Detail resolution range (mm)	Accuracy range (mm)	Ra range (μm)
BJT	0.03–0.064	0.016–0.1	5–15.25
DED	0.1–4	0.1–0.5	6–25
PBF	0.01–0.3	0.05–0.14	1.5–20

The PBF and DED technologies lead to very close density values of the printed parts, however, the seven DED machines showed less variability than the values found in

the PBF, both of which could reach close to 0.999. Figure 4 shows the results obtained through the technical sheets of the machines, including only the equipment that presented the density information.

The density of technologies also varies according to the energy source, as shown in Table 8. The density of DED using an electron beam showed 99% density, while DED with laser can reach 99.65%. With the number of machines analyzed for the PBF, the type of energy source does not have a significant influence, with very close density values for electron beam and laser, being 99.50% and 99.53%, respectively.

4.3 Surface Finish

The surface finish for the analysed machines presented higher values for the DED process, followed by PBF and BJT. Typical surface roughness values for each process are 10–16 μm for PBF, 40 μm for DED with thin layer thickness and minimal deposition speed, and up to 90 μm with decreased resolution and maximal building rate [133]. According to Wohlers (2019) the average roughness of BJT, PBF, and DED respectively are 10 μm , 11 μm , and 17.5 μm .

In this graph, machines were analyzed without considering energy sources and using the best values that the machine can produce (lowest value of the range). Figure 5 shows the maximum value for DED of 12 μm , 10 μm for PBF, and 5 μm for BJT. The BJT presented an outlier value of 15 μm for the ExOne Innovent X machine. The minimum values found for DED, PBF, and BJT are 9 μm , 2 μm , and 4 μm , respectively. The minimum outlier value for DED refers to BeAM's Magic 800 machine.

The surface finish values depend on the process factors, such as the deposition rate, layer thickness, working temperature, the powder granulometry, among others. Surface finish in additive manufacturing processes often depends strongly on the part's orientation during printing. For example, the downskin surface, which is the surface in direct contact with the build platform or support structures, tends to have a higher roughness compared to other surfaces. This occurs because the initial layers of material adhere to the platform or supports, and their texture can influence the finish of the final part.

Designing the orientation of a part can be a crucial consideration in additive manufacturing to achieve the desired surface finish and mechanical properties. Adjusting the orientation may help minimize the impact of rough surfaces on critical areas of the part.

DED, in general, has higher deposition rates compared to other MAM and, therefore, higher surface finish values, being necessary post-processing to improve the surface finish.

4.4 Raw material

Technology availability can be seen in terms of the materials that can be produced by each technology, often limiting the technology because meeting the design requirements is linked to the mechanical and physical properties of the selected material.

Currently, there is a high variety of metals available for AM production. However, the option is wider for PBF and DED technologies (see Fig. 6). The current development of equipment by manufacturers allows the inclusion of new

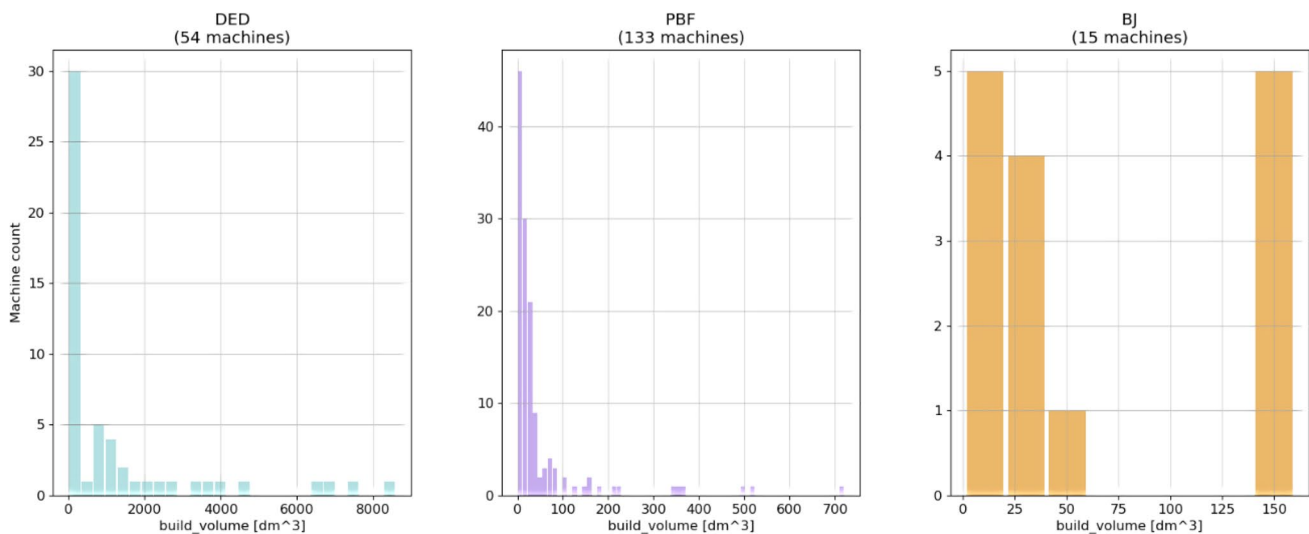


Fig. 9 Build volume according to metal additive technology

Table 10 Multi-material capability

Technologies	Companies	Multi-material
DED	BeAM	Yes
	Sciaky	Yes
	DMG Mori	Yes
	Optomec, LENS	Yes
	Trumpf Laser	Yes
	Norsk Titanium	Yes
	Gefertec	Yes
	Addilan	Yes
BJT	Digital Metal	No
	HP Inc	No
	Desktop Metal	No
	ExOne	No
PBF	EOS GmbH	No
	3D System	No
	Arcam AB	No
	Aerosint	Yes
	QuickBeam Tech.Co	No
	Matsuura	No
	OPM Lab	No
	Concept Laser GmbH	No
	Trumpf GmbH + Co. KG	No
	Sisma S.p.A	No
	Additive Industries	No
	Renishaw	No
	Bright Laser Technologies	No
	DMG Mori	No
	Eplus 3D	No
	Farsoon	No
	Huake 3D	No
SLM Solutions GmbH	No	
Xact Metal	No	
Aconity3d GmbH	Yes	

materials and therefore, the scenario can change with the improvement of technologies.

As shown in Fig. 6, the dashed area corresponds to the area of metallic materials, and the circular region is the number of equipment analyzed from the different technologies that can produce parts with the selected materials. The positioning of the materials in the graph corresponds to the approximate centroid values of Young's modulus and density of the presented alloys. The values which AM can produce in terms of metals are vast and considerable.

4.5 Minimum detail resolution

Detail resolution is the level of detail and complexity that manufacturing technologies can produce. The PBF and BJT additive technologies are capable of manufacturing parts

with a high level of detail, reaching minimum values of 0.01 mm for PBF.

However, as can be seen in Fig. 7, DED has a more homogeneous distribution, and, in general, DED has a larger nozzle diameter, which allows it to have a higher deposition rate on the other hand, reduces the detailing resolution of the parts.

The BJT is the technology with the smallest range of values with high detail resolution. Disregarding the outliers, the DED ranges from 0.1 to 1.6 mm, the PBF ranges from 0.01 to 0.30 mm, and the BJT from 0.03 to 0.065 mm for the set of machines analyzed.

4.6 Minimum dimensional accuracy

Accuracy shows the technology's ability to achieve rigorous dimensional tolerances, that is, the ability to accurately produce the dimensions required in the original file of the project. Among the three technologies analyzed, BJT has the highest dimensional accuracy, with minimum values close to 0.016 mm. It is important to note that challenges persist regarding the uncontrolled and not entirely predictable anisotropic shrinkage observed in parts. As shown in Fig. 8, the PBF presented a more homogeneous distribution of data, despite having outliers with values of 0.2 and 0.4 mm, respectively.

The DED presented values between 0.1 and 4 mm, with a greater variation in the dimensions compared to other technologies. Table 9 presents the general values of the selection criteria for detail resolution, accuracy, and surface finish. The values include all data found from the equipment, not just the smallest values in the range.

4.7 Build volume

The build volume shows the availability of technologies in terms of the maximum size the part can be manufactured. The number of equipment analyzed also allows us to understand which technologies have the greatest availability of equipment on the market. For this selection criterion, 58 DED machines, 128 PBF machines, and 15 BJT machines were analyzed to assess the maximum build volume allowed by the technologies.

Figure 9 shows the build volume for the equipment regarding the three technologies. The PBF has a significant number of equipment with a diverse range of build sizes. In addition, most of them are available in build sizes smaller than 200 mm³ but can reach 700 mm³ build volume.

DED build size has much higher values compared to other technologies, the machines can reach build volumes above 8000 mm³, with a large volume of equipment with sizes below 2000 mm³. The equipment with high build volume values uses gantry structures, which allow movement along

Table 11 Additive technology process time. (1) lowest process time, (2) medium process time, (3) highest process time, and –) the technology does not have this stage

Stages	Process Time		
	Binder Jetting	Directed Energy Deposition	Powder Bed Fusion
Part design	1	1	2
Software build setup	1	1	1
Machine setup	2	1	2
Printing	1	2	3
Cure	1	-	-
Build removal	2	1	2
Sintering	1	-	-
Infiltration	1	-	-
Remove supports	-	-	1
Machining	1	2	1
Heat treatment	1	1	1
Surface finish	1	2	1

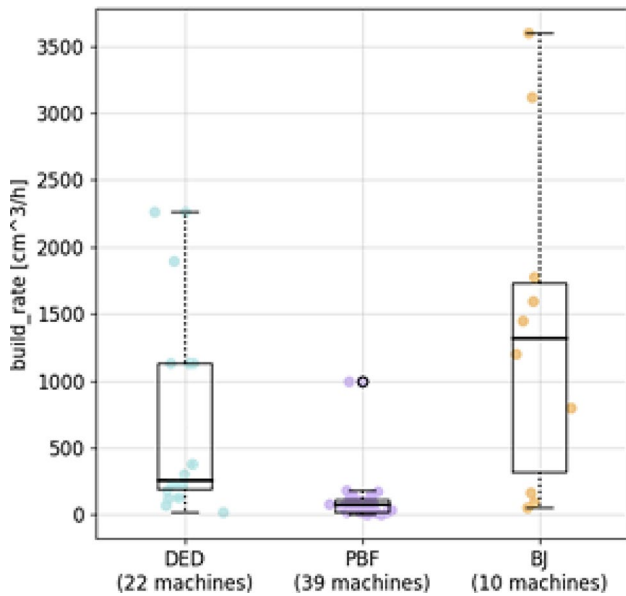


Fig. 10 Build rate of the MAM

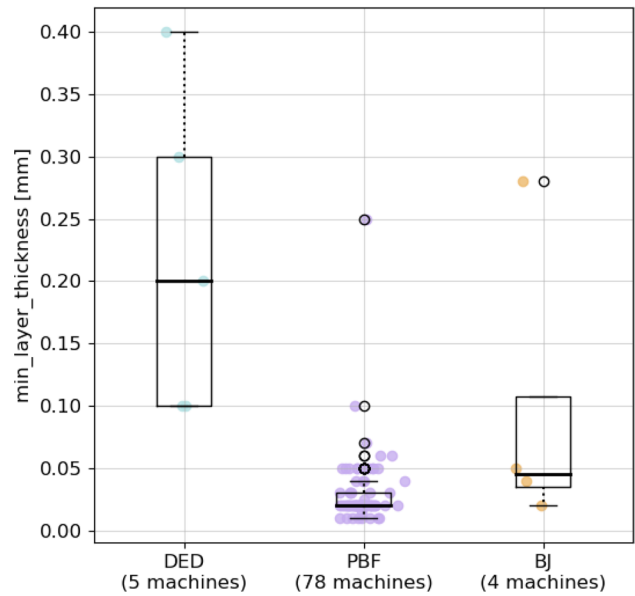


Fig. 11 Minimum Layer Thickness

the horizontal axis. The BJT technology has limited equipment options currently in the market, primarily consisting of small and medium-sized machines with a maximum build size reaching 160 mm³ (see Fig. 9).

4.8 Multi-material

The use of processes with the inclusion of different materials is a differential that allows greater freedom of design with complex geometric projects and with increased multifunctionality, with properties like hardness, corrosion resistance,

and environmental adaptation that may be specified in locations where they are most needed.

So far, among the technologies analyzed, the ones that have equipment that allows the use of multi-material are DED and PBF, in greater numbers for DED processes (see Table 10). The BJT still does not have any equipment on the market capable of producing multi-material, however, the technology is developing rapidly.

4.9 Process time

As explained in Sect. 3.4.1., Table 11 was developed to compare the three technologies for each stage of the manufacturing process. The processing time is distributed on a scale of 1–3, where 1 is the smallest process time value and 3 is the highest value of process time to carry out the step. Steps that are not part of the technology process are designated with a (-) sign. The table was built based on the literature, articles on the technologies, and technical magazines of the equipment [38, 40, 53, 55, 63, 64, 134–141].

Table 11 shows the step in a generalized way, that is, what usually happens in the processes, but each step depends a lot on the parameters used in the machine, the material used, the orientation of the part in the build plate, and the performance of the equipment in question.

In general, the technology with the shortest processing time is DED, followed by PBF and BJT. Comparing only the printing phase, the technology that demands the most time is PBF. The steps that require more time in PBF compared to other technologies are part design, printing and supports removal.

Regarding the analysis of post-processing, it is possible to see that BJT needs more steps to achieve mechanical resistance values comparable to those of DED and PBF. In BJT, despite being able to manufacture the parts with less process time, they necessarily need sintering, which often requires more time than the printing process itself.

The DED process, despite being faster, can be time-consuming in the machining and surface finish processes due to the excess thickness needed to ensure that the final part has

surface finish properties and dimensional tolerances suitable for the project requirements.

4.10 Build rate

The data collected from the machines demonstrates the disparity of build rate values between the MAM technologies. The analysis used the maximum build rate values of the selected equipment (see Table 11), and only two of the twenty-two DED machines analyzed refer to the WAAM process.

The BJT values are considerably higher compared to others MAMs because its powder joining process is done with the bonding agent without using an energy source for melting the powder particles. This allows for higher speed in the construction of the part, but the construction of the component is done only through the physical union of the powder, requiring debinding and sintering stage to reach proper density and mechanical strength. The minimum build rate value found was 54 cm³/h (Innovent X), and the maximum was 3600 cm³/h (X1 25PRO).

The values found for the DED also demonstrate a wide build rate range. One way of manufacturing the DED is to introduce the powder simultaneously as the laser melts it, thus speeding up the production process. In DED, the melting material is deposited using focused thermal energy such as a laser, electron beam, or plasma arc. These particularities generate differences in the build rate; for example, the highest build rate values are associated with WAAM machines. These machines use an electric arc to melt the wire, producing the component without introducing powder.

Table 12 Cost per unit of volume (CUV)

Process	Machine	Material	SEC (kWh/kg)	Build rate (cm ³ /h)	Print Power (W)	€/cm ³	EI (pt/kg)	Average €/cm ³	Literature
PBF	MTT SLM250	316L	38.75	7.09	200	4.67	1.103	2.52	[143–146]
PBF	Concept Laser M3	316L	163.33	6.80	105	3.51	3.718		[17, 143, 145]
PBF	Concept Laser M2	316L	26.89	35	800	0.96	0.854		[17, 143, 147]
PBF	Concept Laser Mlab	AlSi10Mg	148.06	5	100	1.85	3.565		[17, 143, 145]
PBF	Renishaw AM250	AlSi10Mg	157.28	20	200	0.70	3.759		[143, 145, 148]
PBF	Arcam AB	Ti-6Al-4 V	30.56	20.14	3,000	1.18	2.552		[143–145, 148]
PBF	EOSINT M 270	SS 17–4 PH	94.17	64.1	200	4.80	2.266		[143, 146, 149]
DED	Optomec LENS 750	316L	292.22	63.3	1,000	0.98	6.425	1.06	[46, 143, 149, 150]
DED	Optomec LENS 850R	Ti-6Al-4 V	584	113.1	2,000	1.14	14.174		[143, 149, 150]
BJT	EPRI 2014	316L	23.06	0.82	500	22.20	1.841	22.20	[145, 151, 152]

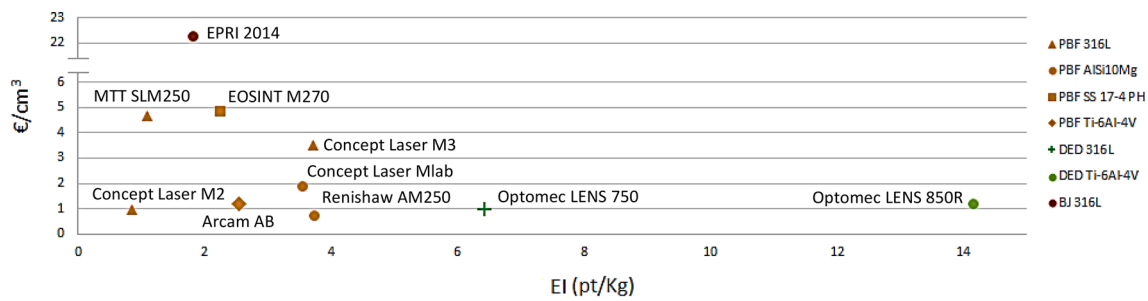


Fig. 12 Environmental impact versus cost per unit volume (CUV)

The intermediate build rate values found in the DED analysis, ranging from 1131 to 1894 cm³/h, are from equipment using an electron beam as thermal energy. Most of the equipment that uses laser showed values between 20 and 379 cm³/h.

The build rates for DED tend to be a little higher than PBF. According to Timothy Simpson (2019)[142], the laser spot size for DED is at least ten times larger than what is utilized in PBF. As a result, there is a bigger melt pool target for the powder to hit and melt against. The laser's scan speed, the energy absorption, and the thermal conductivity of the feedstock deposited are all factors that influence the depth and speed of the resulting melt pool in DED.

The PBF has range values from 4 to 1000 cm³/h, lower than in other MAM technologies, as the following layer can only start once the previous one has been covered with powder. The build rate values between the laser and electron beam machine showed ranges from 4 to 1000 cm³/h and 35 to 120 cm³/h, respectively. Compared to a laser, an electron beam may reach deeper into the powder grains, causing a more uniform melting of the powder. In terms of build rate, laser machines can produce at a higher rate than electron beam machines (see Fig. 10).

4.11 Layer thickness

The notable variation in layer thickness values in the DED technology compared to other MAM technologies (see Fig. 11). One possible reason for this significant variation may lie in the versatility of the DED process. DED allows for a wide range of operational configurations, providing operators with the flexibility to adjust layer thickness according to specific project requirements. This contrasts with some other MAM technologies, which may have more rigid settings and less adaptability in terms of layer thickness. Furthermore, a study of the nozzle dimensions can also contribute to understanding this variation. If the nozzle dimension is relatively larger in DED compared to other MAM technologies, it can directly influence material deposition, potentially resulting in thicker layers.

The PBF showed a relatively smaller layer thickness compared to DED and BJT. This is due to the nature of the PBF process, in which a thin layer of metal powder is evenly distributed on the build platform and then a laser or electron beam is used to selectively melt the powder layer in specific areas, creating a single solid layer. Due to the precision of these focused energy beams, PBF allows the creation of extremely thin layers, often in the micrometer range. These extremely thin layers allow to produce parts with high resolution and detail, making PBF a preferred choice for applications requiring tight tolerances and high-quality surface finishes.

However, it is important to note that layer thickness can also be influenced by machine capacity, the type of material in use and specific project configurations. Thinner layers generally result in a slower process, while thicker layers can speed up production.

BJT can create relatively thin layers, although these layers can be slightly thicker compared to L-PBF and EBM. In BJT systems, the layer thickness can be adjusted to values that generally range from around 50 μm to 100 μm. However, it is worth noting that some more advanced BJT systems may be able to create thinner layers, while others may be limited to slightly thicker layers.

4.12 Environmental Impact (pt/kg) and Cost per unit of volume (CUV)

The analysis of the environmental impact as a selection criterion for an initial phase of the project considers only the printing phase of each technology and accounts for the impact of energy and material. Despite being a simplified analysis, it is possible to use it at the early design and technology selection phases. The energy consumption depends on several equipment factors, such as laser power, rate, manufacturing time, and the type of material used, but in this analysis, the SEC (specific energy consumption) values available in the literature were used (see Table 12). The Cost per unit of volume (CUV) selection criterion is also shown in Table 12. All values considered for the analysis

were taken from the literature, as result, only the materials described in the table were studied for greater accuracy of the results. It is also possible to comparatively analyze the EI as a function of the cost per volume unit, as illustrated by Fig. 12.

In terms of material, it is possible to verify that for the manufacture of the 316L in the three technologies, the highest EI found was for the DED using Ti-6Al-4V as material, this is mainly due to the high value of SEC for manufacturing in titanium alloys. BJT and followed by PBF showed lower values for EI if we consider the Optomec LENS 750, EPRI 2014, and Concept Laser M3 equipment respectively. Results also showed that what main influences of the EI values are the SEC and build rate value, as they are directly related to energy consumption and process time. In terms of technologies, the DED has a higher environmental impact value in both analyzed materials, due to the high specific energy consumed by the equipment, for laser power between 1000 and 2000W.

Data on BJT technology regarding SEC (kWh/kg) and build rate (kg/h) are still scarce and need further investigation. The highest value found for CUV was for the BJT using the 316L, reaching a value of 22.2 €/cm³, which is directly related to the low build rate found in the literature. Further investigation and comparison with other materials are necessary to have a more realistic analysis of the process.

The SEC values vary greatly according to the equipment, considering the power of the laser and the material used. The PBF presented the CUV value of 4.80 €/cm³ using the SS17-4 PH and EOSINT M 270 machine.

Regarding costs, The BJT had the highest cost value per volume unit, despite having a lower SEC. This is due to having a build rate value much lower compared to the PBF and DED, around 84% lower.

5 Conclusions

This paper proposes a framework to analyse the technological capability of metal additive technologies through the identification of competitive criteria of parameters of interest, followed by an exhaustive review of the values found in commercial equipment. This allows the comparison of MAM technologies and the establishment of current limits and ranges of each one of them.

The results indicate that, in general, when analyzing the printing step, the technologies with the greatest capacity for detail and precision are PBF and BJT, respectively. Therefore, being more suitable for parts with a higher level of design complexity and greater dimensional tolerance.

The technologies that presented very close density, reaching 100% in some cases, were DED and PBF. This feature

is especially important for structural parts where greater fatigue strength is required.

The availability in terms of materials for manufacturing today, as well as the possibility of manufacturing by multi-material, has a greater limitation for the BJT process, having a greater number of equipment and materials available for the DED processes.

The roughness of the processes showed a higher value for DED compared to other technologies, requiring a more significant number of post-processing depending on the application of the part. The technology that presented the best surface finish was the PBF.

All the previous results are well-established, being documented quantitatively in catalogues and literature. The novelty is being digested and arranged in a visual and comparative format, providing a clear and concise overview. This exercise provides general conclusions regarding the process time, cost per unit of value, and environmental impact.

The study of the process time was unfolded in two steps, one qualitative considering all steps required in each MAM technology and one quantitative, for mapping the current achievable build rate with available equipment. The qualitative analysis showed that the technology that demands the longest production time is the BJT if we compare all the stages of the process time use of equipment impacts the values of energy consumed.

In terms of cost per unit of volume, the preliminary assessment proposed showed higher values for BJT and PBF, which may change with the evolution of technology, the availability of more efficient equipment, and a lower cost of materials.

Regarding the environmental impact, the process with higher EI was DED using Ti-6Al-4V, mainly due to the high value of SEC for manufacturing titanium alloys.

The work presented some limitations due to the absence of data in the technical files and literature related to the proposed selection criteria. Furthermore, the data present very large variations and generalization may alter the results presented. Unlike consumption products like cell phones or computers, well-defined benchmarks do not exist, one of the reasons for this paper. Also, due to the high costs of installation and operations, replications or external reviews are scarce. In this work, data is accepted at face value. Validation was done by redundant search of values through multiple sources (papers and reports) apart from the company's catalogues, when possible. A more expressive amount of data is still needed to obtain a deeper and more interesting benchmark of these technologies. In the future, databases of equipment and capabilities are to have validation from multiple sources, as well as the completeness of data for major categories identified in this work.

In addition, a greater number of SEC studies of different materials and equipment with different laser power capabilities is necessary to assess the environmental impact and cost associated with these processes and include all stages of the process time in these assessments. Some materials, namely nickel-based alloys were not included

in the results due to this limitation in data collection. The potential to reuse and/or recycling of AM powders is crucial for their environmental and economic viability. Future studies should focus on these topics, assessing their technological impacts on mechanical properties.

Appendix I. Metal additive manufacturing data

Binder Jetting								
Brand	Model	Raw material	Build volume [dm]	Detail Capability [mm]	Density [g/cm ³]	Surface Finish (Ra)	Dimensional Accuracy [mm]	Build rate [cm ³ /h]
Desktop Metal	Production System P1	–	0.8	–	–	–	–	–
Desktop Metal	Production System P50	–	48.41	–	–	–	–	–
Desktop Metal	Shop System	–	15.4	0.05	–	–	0.016	800
Desktop Metal	X160Pro	–	160	–	–	–	–	–
Desktop Metal	X25Pro	–	25	–	–	–	–	–
Digital Metal	DMP PRO	–	–	–	–	–	–	–
Digital Metal	DMP 2500	Stainless Steel Alloys, titanium alloys, steel alloys, and nickel alloys	2.99943	0.035	0.96	5	0.035	100
EASYMFG	Easy3DPM450	–	160	–	–	–	–	–
EASYMFG	Easy3DPM500	–	–	–	–	–	–	–
ExOne	SPrint	–	160	–	–	–	0.1	–
ExOne	Innovent X	Stainless steel alloys, copper alloys, and cobalt chrome alloys	0.676	0.0635	0.97	15	0.1	54
ExOne	Innovent +	–	0.676	0.03	–	4	–	166
ExOne	X25PRO	Nickel alloys, steel alloys, and stainless steel alloys	25	0.03	–	–	0.03	1200
ExOne	X1 25PRO	–	–	–	–	–	–	3600
ExOne	S-Max	–	–	–	–	–	–	–
ExOne	M-Flex	–	25	–	–	4	–	1600
ExOne	X160Pro	Nickel alloys, steel alloys, and stainless steel alloys	160	0.03	0.97	–	–	3120
ExOne	MPrint	stainless steel alloys	160	–	–	4	–	1780
GE Additive	H1	–	–	–	–	–	–	–
HP Inc	Metal Jet	–	–	0.05	0.93	–	–	–

Direct Energy Deposition

Brand	Model	Raw Material	Build volume [dm]	Detail Capability [mm]	Density [g/cm ³]	Surface Finish (Ra)	Dimensional Accuracy [mm]	Build rate [cm ³ /h]
Meltio	M450	–	0.01	–	–	–	0.01	–
Aconity3D	3DMetalWIRE	–	0.25	4	–	–	–	–
DMG Mori	LASERTEC 65 3D Hybrid	–	0.31	1.6	–	–	–	379
Meld Manufacturing	L3	–	0.38	–	–	–	–	–
DMG Mori	LASERTEC 65 3D	Stainless steel alloys, steel alloys, nickel alloys, copper alloys, cobalt chrome alloys, copper alloys, and aluminum alloys	0.57	1.2	–	–	–	379
DMG Mori	LASERTEC 4300 3D Hybrid	Steel alloys, nickel alloys, cobalt chrome alloys, and titanium alloys	1.55	1	0.998	10	0.5	226
Optomec	LENS 450	Stainless steel alloys, steel alloys, nickel alloys, titanium alloys, aluminum alloys, and cobalt chrome alloys	3.375	–	–	–	0.25	–
Optomec	LENS CS 150	–	3.375	–	–	–	0.014	–
DMG Mori	LASERTEC 6600 3D	–	5.87	4	–	–	–	–
Optomec	LENS HCTBR	–	15.63	–	–	–	–	–
Optomec	LENS CS 250	–	15.63	–	–	–	0.001	–
BeAM	Mobile	–	20	0.8	–	–	0.1	70
Optomec	LENS MR7	Steel alloys, stainless steel alloys, titanium alloys, nickel alloys, cobalt chrome alloys, aluminum alloys, and copper alloys	27	0.25	–	–	0.25	–
Optomec	LENS 750 v_0	–	27	0.25	–	–	0.25	–
Optomec	LENS 750 v_1	–	27	0.25	–	–	0.25	–
DM3D	DMD IC106	–	27	–	–	–	–	–
INETYX	AMW300X	–	27	–	–	–	–	–
BeAM	Modulo 250	–	30	0.8	–	–	0.1	20
DigitalAlloys	Joule Printing metal 3D printer	–	40	–	–	–	–	–

Direct Energy Deposition

Brand	Model	Raw Material	Build volume [dm]	Detail Capability [mm]	Density [g/cm ³]	Surface Finish (Ra)	Dimensional Accuracy [mm]	Build rate [cm ³ /h]
InssTek	MX400	Stainless steel alloys, steel alloys, and nickel alloys	54	–	–	–	–	–
Optomec	LENS MTS 500	–	81.25	–	–	–	0.005	–
Optomec	LENS CS 600	–	96	–	–	–	0.02	–
InssTek	MX600	Stainless steel alloys, steel alloys, and nickel alloys	102.6	–	–	–	–	–
BeAM	Modulo 400	–	104	2	–	–	0.2	130
Norsk Titanium	MERKE 4	–	162	–	–	–	–	2262
Trumpf	TruLaser 3000	Stainless steel alloys, steel alloys, nickel alloys, titanium alloys, aluminum alloys, copper alloys, and cobalt chrome alloys	192	–	–	–	–	–
RPM Innovations	LMD 222	stainless steel alloys, nickel alloys, and titanium alloys	216	–	–	–	–	226
DM3D	DMD 105D	–	275.2	–	–	–	–	–
Optomec	LENS CS 800	–	288	–	–	–	0.02	–
Optomec	LENS MTS 860	–	314.76	–	–	–	0.005	–
InssTek	MX1000	Stainless steel alloys, steel alloys, and nickel alloys	520	–	–	–	–	–
Gefertec	arc403	–	720	–	–	–	–	–
BeAM	Magic 800	Stainless steel alloys, steel alloys, titanium alloys, nickel alloys, copper alloys, and cobalt chrome alloys	768	2	–	6	0.2	130
BeAM	Magic 2.0	–	768	2	–	–	–	300
DM3D	DMD 505D	–	891.5766	–	–	–	–	–
DMG Mori	LASERTEC 125 3D	–	914.25	–	–	–	–	226
BeAM	Magic 1.0	–	960	0.6	–	–	–	180
ADDere	SYSTEM I	–	1000	–	–	–	–	–

Direct Energy Deposition

Brand	Model	Raw Material	Build volume [dm]	Detail Capability [mm]	Density [g/cm ³]	Surface Finish (Ra)	Dimensional Accuracy [mm]	Build rate [cm ³ /h]
Optomec	LENS 850R	Steel alloys, stainless steel alloys, titanium alloys, nickel alloys, cobalt chrome alloys, aluminum alloys, and copper alloys	1215	0.5	0.99	12	0.25	–
Optomec	LENS CS 1500	–	1215	–	–	–	0.186	–
DM3D	DMD 44R	–	1482.57	–	–	–	–	–
Sciaky	EBAM 88	Titanium alloys	1733.91	–	–	–	–	1131
ADDere	SYSTEM II	–	2000	–	–	–	–	–
RPM Innovations	LMD 535	Stainless steel alloys, nickel alloys, and titanium alloys	2250	–	–	–	–	226
Gefertec	arc603	Steel alloys, nickel alloys, aluminum alloys, copper alloys, titanium alloys, and magnesium alloys	2648.8	0.6	0.99	10	0.1	–
Sciaky	EBAM 110 Series	Titanium alloys	3396.6912	–	0.99	–	–	–
Sciaky	EBAM 68	Titanium alloys	3507.948026	–	–	–	–	1131
InssTek	MXGrande	Stainless steel alloys, steel alloys, and nickel alloys	4000	–	–	–	–	–
RPM Innovations	LMD 557	Stainless steel alloys, nickel alloys, and titanium alloys	4725	–	–	–	–	226
DM3D	DMD 66R	–	6498.137	–	–	–	–	–
Sciaky	EBAM 150 Series	Titanium alloys	6930.86625	–	–	–	–	1131
Sciaky	EBAM 200	Titanium alloys	7395.08	–	–	–	–	1131
Sciaky	EBAM 300 Series	Steel alloys, titanium alloys, nickel alloys, and tantalum alloys, tungsten alloys, stainless steel alloys, aluminum alloys, nickel alloys, and niobium alloys	8605.200151	–	0.99	–	–	–
ADDere	SYSTEM III	–	640,000	–	–	–	–	–
Sciaky	EBAM 40	Titanium alloys	–	–	–	–	–	1894

Direct Energy Deposition

Brand	Model	Raw Material	Build volume [dm]	Detail Capability [mm]	Density [g/cm ³]	Surface Finish (Ra)	Dimensional Accuracy [mm]	Build rate [cm ³ /h]
Norsk Titanium	WAAM	Titanium alloys, nickel alloys, steel alloys, and stainless steel alloys	–	–	0.99	–	–	2262
Trumpf	TruPrint 3000	Stainless steel alloys, steel alloys, aluminum alloys, nickel alloys, and titanium alloys	–	–	–	–	–	120
Addilan	Addilan v0.1	Steel alloys, titanium alloys, and aluminum alloys	–	–	0.99	–	–	–
Trumpf	TruLaser 7040	Stainless steel alloys, steel alloys, nickel alloys, titanium alloys, aluminum alloys, copper alloys, and cobalt chrome alloys	1575	–	–	–	0.08	–

Powder Bed Fusion

Brand	Model	Metal Type	Build volume [dm]	Detail Capability [mm]	Density [g/cm ³]	Surface Finish (Ra)	Dimensional Accuracy [mm]	Build rate [cm ³ /h]
EOS	EOS M 100	Cobalt chrome alloys, stainless steel alloys, and titanium alloys	0.7461282552	–	–	–	–	4
Concept Laser GmbH	MLab Cusing	–	0.65	–	–	–	–	5
Eplus3D	EPM150	–	2.12	–	–	–	–	12.75
TRUMPF	TruPrint 1000	Stainless steel alloys, steel alloys, aluminum alloys, nickel alloys, titanium alloys, copper alloys, silver, gold, and copper alloys	1	–	–	–	–	18
Concept Laser GmbH	M2 Cusing	Cobalt chrome alloys, stainless steel alloys, titanium alloys, aluminum alloys, and steel alloys	17.5	0.1	0.995	4.5	0.05	20
EOS	EOS M 280	Cobalt chrome alloys, stainless steel alloys, titanium alloys, steel alloys, nickel alloys, aluminum alloys	21.875	–	–	–	–	20

Powder Bed Fusion

Brand	Model	Metal Type	Build volume [dm]	Detail Capabil-ity [mm]	Density [g/cm ³]	Sur- face Finish (Ra)	Dimen- sional Accuracy [mm]	Build rate [cm ³ /h]
Realizer	SLM Realizer 125		3.125	–	–	–	–	20
Renishaw	RenAM 250	Cobalt chrome alloys, titanium alloys, stainless steel alloys, steel alloys, nickel alloys, and aluminum alloys	22.8125	–	–	–	0.07	20
Renishaw	RenAM 400	Cobalt chrome alloys, titanium alloys, stainless steel alloys, steel alloys, nickel alloys, and aluminum alloys	18.75	–	–	–	–	20
Renishaw	RenAM 500E		21.875	–	–	–	–	25
SLM Solutions	SLM 125 HL		3.125	–	–	–	–	25
EOS	EOS M 290	Cobalt chrome alloys, stainless steel alloys, titanium alloys, steel alloys, nickel alloys, and aluminum alloys	20.31	–	–	–	–	27
GE Additive	Arcam EBM Spectra H		21.11	–	–	–	–	35
Matsuura	LUMEX Avance25	Steel alloys, stainless steel alloys, titanium alloys, cobalt chrome alloys, nickel alloys, and aluminum alloys	12.12416	–	–	–	–	35
Matsuura	LUMEX Avance60	Steel alloys, stainless steel alloys, titanium alloys, cobalt chrome alloys, nickel alloys, and aluminum alloys	180	–	0.999	–	–	35
SLM Solutions	SLM 250 HL	–	21.875	–	–	–	–	45
Eplus3D	EPM260	–	27.59	–	–	–	–	55
Arcam	ARCAM EBM S12	–	7.2	–	–	–	–	60
Eplus3D	EPM450	–	103.51	–	–	–	–	65
Arcam	Arcam A2	Titanium alloys and cobalt chrome alloys	25	–	–	–	–	80
Arcam	Arcam A1	Titanium alloys and cobalt chrome alloys	7.2	–	–	–	–	80
GE Additive	Arcam EBM Spectra Q10Plus v2.0	Titanium alloys, cobalt chrome alloys, and nickel alloys	7.2	–	–	–	–	80
SLM Solutions	SLM 280 HL	Cobalt chrome alloys, titanium alloys, stainless steel alloys, steel alloys, nickel alloys, and aluminum alloys	28.616					88

Powder Bed Fusion

Brand	Model	Metal Type	Build volume [dm]	Detail Capability [mm]	Density [g/cm ³]	Surface Finish (Ra)	Dimensional Accuracy [mm]	Build rate [cm ³ /h]
DMG Mori	LASERTEC 30 DUAL SLM	Cobalt chrome alloys, titanium alloys, stainless steel alloys, steel alloys, nickel alloys, and aluminum alloys	27	0.1	0.995	10	0.05	90
ADIRA	AddCreator	–	500					100
EOS	EOS M 400	Cobalt chrome alloys, stainless steel alloys, titanium alloys, steel alloys, nickel alloys, and aluminum alloys	64					100
EOS	EOS M 300	Steel alloys, stainless steel alloys, cobalt chrome alloys, titanium alloys, copper alloys, nickel alloys, and aluminum alloys	36	0.3	0.99	9	0.05	100
SLM Solutions	SLM 500 HL	–	51.1					105
EOS	EOS M 400–4	Stainless steel alloys, cobalt chrome alloys, and Copper Alloys	64				0.1	107
Concept Laser GmbH	Xine 2000 R	Aluminum alloys, titanium alloys, nickel alloys	160					120
Eplus3D	EPM650	Titanium alloys, aluminum alloys, nickel alloys, and steel alloys	343.22					120
GE Additive	Arcam EBM Spectra Q20Plus	Titanium alloys, cobalt chrome alloys, nickel alloys, and copper alloys	36.56	0.25	0.99	10	0.2	120
Additive Industries	MetalFAB G2	–	70.56					150
Renishaw	RenAM 500M	Cobalt chrome alloys, titanium alloys, stainless steel alloys, steel alloys, nickel alloys, and aluminum alloys	21.875					150
Renishaw	RenAM 500Q	Stainless steel alloys, titanium alloys, cobalt chrome alloys, steel alloys, nickel alloys, and aluminum alloys	20.11					150
SLM Solutions	SLM 800	Cobalt chrome alloys, titanium alloys, stainless steel alloys, steel alloys, nickel alloys, and aluminum alloys	81.76					171
ADIRA	AddCreator AC210	–	520.2					180

Powder Bed Fusion

Brand	Model	Metal Type	Build volume [dm]	Detail Capabil-ity [mm]	Density [g/cm ³]	Sur-face Finish (Ra)	Dimen-sional Accuracy [mm]	Build rate [cm ³ /h]
Additive Indus-tries	MetalFAB600	–	360					1000
SLM Solutions	NXG XII 600	Cobalt chrome alloys, titanium alloys, stainless steel alloys, steel alloys, nickel alloys, and aluminum alloys	216					1000
3D MicroPrint	DMP50 GP	–						
3D MicroPrint	DMP60 series	–	0.08					
3D Systems	ProX DMP 200	Cobalt chrome alloys, steel alloys, stainless steel alloys, and aluminum alloys	1.96	0.1			0.02	
3D Systems	ProX DMP 200 Dental	Cobalt chrome alloys, steel alloys, stainless steel alloys, and aluminum alloys	1.96				0.02	
3D Systems	ProX DMP 300	Cobalt chrome alloys, steel alloys, stainless steel alloys, and aluminum alloys	20.625					
3D Systems	ProX DMP 320	Titanium alloys, nickel alloys, cobalt chrome alloys, steel alloys, stainless steel alloys, and aluminum alloys	31.7625				0.02	
3D Systems	DMP Dental 100	Cobalt chrome alloys	0.81				0.05	
3D Systems	DMP Flex 100	Cobalt chrome alloys, and stainless steel alloys	0.8				0.02	
3D Systems	DMP Flex 350	–	28.74					
3D Systems	DMP Factory 350	Stainless steel alloys, steel alloys, cobalt chrome alloys, titanium alloys, alu-minum alloys, gold, and silver	31.7625	0.1	0.99		0.05	
3D Systems	DMP Factory 500	–	125					
3D Systems	DMP Flex 200	Cobalt chrome alloys, steel alloys, stainless steel alloys, and aluminum alloys	2.25					
3D Systems	DMP Flex 350 Dual	–	31.76					
3D Systems	ProX DMP 100	–	1					
3DSL.A.RU	PRO/ProM	–	15.625				0.002	
3DSL.A.RU	RussianSLM 125/150	–	3.375				0.002	
3DSL.A.RU	RussianSLM 200	–	8				0.002	
3DSL.A.RU	RussianSLM 250	–	15.625				0.002	
3DSL.A.RU	RussianSLM FAC-TORY	–	4.046				0.011	
Aconity3D	AconityMICRO	–						

Powder Bed Fusion

Brand	Model	Metal Type	Build volume [dm ³]	Detail Capability [mm]	Density [g/cm ³]	Surface Finish (Ra)	Dimensional Accuracy [mm]	Build rate [cm ³ /h]
Additive Industries	MetalFAB1	Titanium alloys, aluminum alloys, stainless steel alloys, steel alloys, and nickel alloys	70.56		0.995		0.05	
AddUp	FormUp 350	Titanium alloys, stainless steel alloys, nickel alloys, aluminum alloys, and steel alloys	42.875				0.03	
AddUp	FormUp 200		14.175					
Aerosud/CSIR	Aeroswift		720					
AmPro Innovations	SP330		20				0.05	
AmPro Innovations	SP500		31.25				0.05	
Arcam	Q20		36.56					
Arcam	Q10		7.2					
Arcam	Arcam EBM Spectra A2X	Titanium alloys, cobalt chrome alloys, and nickel alloys	15.2					
Auroraabs	STitanium Pro		10				0.05	
Auroraabs	RMP1		81					
BLT (Bright Laser Technologies)	BLTA300	Titanium alloys, steel alloys, stainless steel alloys	150		0.99			
BLT (Bright Laser Technologies)	S200	Titanium alloys, stainless steel alloys, nickel alloys, aluminum alloys, and steel alloys	4.5					
BLT (Bright Laser Technologies)	S300	Titanium alloys, stainless steel alloys, nickel alloys, aluminum alloys, steel alloys	20					
Chamlion	NCLM2150D		2.120575041					
Chamlion	NCLM2150T		2.120575041					
Chamlion	NCLM2150X	Cobalt chrome alloys, stainless steel alloys	1.489173823				0.1	
Chamlion	NCLM3250D		18.75					
CHIRON	AM Cube							
Concept Laser GmbH	M3						0.01	
Concept Laser GmbH	ATLAS		363					
Concept Laser GmbH	Mine Factory	Stainless steel alloys, titanium alloys, nickel alloys	68					
Dedibot	DS2MIX		4.1905					
Dentas	Arrow		0.57					

Powder Bed Fusion

Brand	Model	Metal Type	Build volume [dm]	Detail Capabil-ity [mm]	Density [g/cm ³]	Sur-face Finish (Ra)	Dimen-sional Accuracy [mm]	Build rate [cm ³ /h]
DMG Mori	LASERTEC 12 DUAL SLM		3.125					
DTM	SinterStation 2000		26.95373115	0.7				
DTM	SinterStation 2500		57.684	0.7			0.15	
EOS	EOS M 250		11.5625				0.05	
EOS	EOS M 270		13.4375					
EOS	EOS M 300–4	Nickel alloys, steel alloys, titanium alloys, aluminum alloys, and stainless steel alloys	36					
Eplus3D	EPM150 Pro		4.24					
Eplus3D	EPM450H		227.73					
Eplus3D		Stainless steel alloys, cobalt chrome alloys, titanium alloys, steel alloys, aluminum alloys, and copper alloys	19		0.999			
Ermaksan	ENAVISION		18.75					
Evobeam	Index							
Farsoon	FS301M	Nickel alloys, copper alloys, stainless steel alloys, steel alloys, aluminum alloys, titanium alloys, and cobalt chrome alloys	37.21		0.99			
Farsoon	FS273M		26.92					
Farsoon	FS271M						0.02	
Farsoon	FS421M							
Fonon	3D FUSION							
Freemelt	Freemelt One							
GE Additive	Arcam EBM Spectra L		0.24					
GE Additive	Conceptaser M2 Series 5		30.0125					
GE Additive	Mine Factory		100					
GE Additive	Mlab		0.648					
GE Additive	Mlab 200R		1					
GE Additive	Mlab R		0.648					
GE Additive	Xine 2000R		160					
Huake 3D	HK M125							
Huake 3D		Titanium alloys, nickel alloys, aluminum alloys, and cobalt chrome alloys	16		0.999		0.1	
Itri	AM100/AM250		1					
JEOL	JAM5200EBM		19.63					
Longer3D	LGS300		26.25					
MarKforged	Metal X		11.88					
MCP Tooling Technologies	SLM Realizer 100		1.5625					

Powder Bed Fusion

Brand	Model	Metal Type	Build volume [dm]	Detail Capabil-ity [mm]	Density [g/cm ³]	Sur-face Finish (Ra)	Dimen-sional Accuracy [mm]	Build rate [cm ³ /h]
Mectronic	3DMAMS 800	Stainless steel alloys, steel alloys, titanium alloys, cobalt chrome alloys, nickel alloys, and aluminum alloys						
MTT	SLM 250		20					
Nikon	LasermeisterM100A		12.47					
Nikon	LasermeisterM101A		2.65					
Nikon	LasermeisterM102A		2.65					
One Click Metal	MPrint		3.38				0.005	
Open Additive	0.01		24.9312					
OPMaboratory	OPM350L	Steel alloys, stain-less steel alloys, nickel alloys, and aluminum alloys	16	0.02	0.997	1.5	0.01	
Prima Additive	Laserdyne 430							
Prima Additive	Print Genius 250		23.3					
QuickBeam Tech.Co		Titanium alloys, cobalt chrome alloys, tantalum alloys, copper alloys, molybdenum alloys, and titanium alloys	49		0.99		0.2	
RPM Innova-tions	RPMI 535XR			0.2	0.998	2	0.05	
Sharebot	metalONE		0.42				0.2	
Sisma	MYSINT100		0.79				0.055	
Sisma	EVEMET 200	Stainless steel alloys, steel alloys, alu-minum alloys, nickel alloys, titanium alloys, copper alloys, silver, gold, and cop-per alloys	6.28		0.995		0.055	
Sisma	MYSINT300	Cobalt chrome alloys, titanium alloys, stainless steel alloys, steel alloys, nickel alloys, and aluminum alloys	36					
Sodick	OPM250L	Stainless steel alloys, steel alloys	15.625					
Sodick	OPM350L	Stainless steel alloys, and steel alloys	42.875					
SondaSys	M150		4.5					
SondaSys	M300		26.25					

Powder Bed Fusion

Brand	Model	Metal Type	Build volume [dm]	Detail Capability [mm]	Density [g/cm ³]	Surface Finish (Ra)	Dimensional Accuracy [mm]	Build rate [cm ³ /h]
TRUMPF	TruPrint 3000	Stainless steel alloys, steel alloys, cobalt chrome alloys, aluminum alloys, nickel alloys, titanium alloys, silver, gold, and copper alloys	36		0.995		0.02	
TRUMPF	TruPrint 2000	Stainless steel alloys, steel alloys, cobalt chrome alloys, aluminum alloys, nickel alloys, titanium alloys, silver, gold, and copper alloys	8					
Tytus3D	AccuMetal		29.79					
Velo3D	Sapphire		77.93					
Wiiibox	SLM150		1.152					
Wiiibox	SLM250		18.75					
Wiiibox	SLM280		26.25					
Xact Metal	XM300C	Stainless steel alloys, steel alloys, cobalt chrome alloys, and copper alloys	27.6606		0.999			
Xact Metal	XM200C		2.05					
Xact Metal	XM200G	Steel alloys, stainless steel alloys, cobalt chrome alloys, nickel alloys, titanium alloys, aluminum alloys, and copper alloys	3.38					
Xi'an Brightaser Technologies	BLTA100	Titanium alloys, stainless steel alloys, nickel alloys, aluminum alloys, and steel alloys						
Xi'an Brightaser Technologies	BLTA300	Titanium alloys, stainless steel alloys, nickel alloys, aluminum alloys, and steel alloys						
Xi'an Brightaser Technologies	BLTS210	Titanium alloys, stainless steel alloys, nickel alloys, aluminum alloys, and steel alloys						
Xi'an Brightaser Technologies	BLTS310	Titanium alloys, stainless steel alloys, nickel alloys, aluminum alloys, and steel alloys						

Powder Bed Fusion

Brand	Model	Metal Type	Build volume [dm]	Detail Capabil-ity [mm]	Density [g/cm ³]	Sur-face Finish (Ra)	Dimen-sional Accuracy [mm]	Build rate [cm ³ /h]
Xi'an Brightaser Technologies	BLTS320	Titanium alloys, stainless steel alloys, nickel alloys, aluminum alloys, and steel alloys						
ZRapid Tech	SLM300		26.25					

Acknowledgements The authors acknowledge Fundação para a Ciência e a Tecnologia (FCT), through IDMEC, under LAETA, project UIDB/50022/2020. Also acknowledge the support of FCT grant (ref: PD/BD/08492/2020).

Funding Open access funding provided by FCTIFCCN (b-on).

Data availability The dataset generated and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

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

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