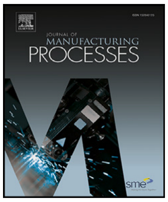
Journal of Manufacturing Processes 128 (2024) 175–189

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

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



Full length article

Metal additive manufacturing adoption in SMEs: Technical attributes, challenges, and opportunities

Mathias Sæterbø [*], Wei Deng Solvang

Department of Industrial Engineering, UiT The Arctic University of Norway, Lodve Langesgate 2, Narvik, 8514, Nordland, Norway

ARTICLE INFO

Keywords:
Metal additive manufacturing (MAM)
Small- and medium-sized enterprises (SMEs)
Technology implementation
Decision making

ABSTRACT

Recent advancements in Metal Additive Manufacturing (MAM) are transforming manufacturing. Most research and market adoption of MAM have focused on Powder Bed Fusion (PBF), with less attention given to Directed Energy Deposition (DED), Binder Jetting (BJ), and Metal Material Extrusion (MEX), which are only now reaching industrial readiness. This increased availability of MAM processes provides SMEs with a wider range of options, opening up new opportunities that were previously inaccessible. However, despite recent technological improvements that broaden potential applications, the suitability of these processes for industrial use by SMEs is not yet well understood. SMEs currently face difficulties in adopting MAM due to complexities and costs. Moreover, existing literature often overlooks the distinct characteristics and needs of SMEs, making it challenging for them to identify the most suitable MAM processes. This study addresses this gap by using a fuzzy logic approach to evaluate the technical characteristics of PBF, DED, BJ, and MEX, focusing on their compatibility with SME requirements. Each process is ranked based on criteria including costs, complexity, energy consumption, mechanical quality, geometrical quality, speed, and market demand. This evaluation is refined through logarithmic normalization and scaling, resulting in a comprehensive scoring system from 1 to 5. Based on these findings, an SME-focused evaluation matrix is proposed to guide SMEs in selecting the most appropriate MAM process for their specific contexts. This matrix promotes informed and effective adoption strategies, supported by practical examples illustrating the application of each MAM process in SME environments.

1. Introduction

Additive Manufacturing (AM) has revolutionized the way we create and think about manufacturing. Its essence lies in the layer-by-layer deposition of material, orchestrated by digital blueprints from CAD models [1]. AM, specifically its subset, Metal Additive Manufacturing (MAM), introduces a novel method distinctly different from traditional subtractive or formative manufacturing techniques. The evolution of MAM represents a significant shift in the manufacturing paradigm, unlocking a range of advancements previously thought unattainable. With MAM, the palette of materials has expanded [2], design optimization has seen breakthroughs, and supply chains have been reimagined [3]. MAM's ability to craft intricate geometries with reduced waste and quicker production timelines has resonated across sectors, such as aerospace, healthcare, automotive, and consumer goods [4–7].

The adoption of MAM, however, has been asymmetric across different scales of industry. Large enterprises (LEs), with extensive resources and R&D capabilities have been quick to adopt MAM. Their investments in state-of-the-art equipment and expertise have solidified their position as front runners in harnessing MAM's potential. Small and Medium-sized Enterprises (SMEs) face a markedly different landscape. Despite MAM's potential, its adoption among SMEs has been limited. Their smaller scale of operation often means missing out on the economies of scale that benefit larger enterprises. This is compounded by the dynamic and rapidly evolving landscape of MAM, which requires continuous upskilling, which can be particularly challenging for SMEs lacking dedicated R&D departments. Additionally, SMEs face additional hurdles such as tighter resource constraints, limited access to advanced technical expertise, and an inherent risk aversion due to the substantial investments required for MAM [8].

Most of the existing literature primarily focuses on AM adoption in large corporations with only a marginal emphasis on SMEs [9], often overlooking the unique challenges and opportunities presented to SMEs. For instance, studies by Mellor et al. [10], Deradjat et al. [11], and Niaki [12] primarily address AM implementation in the context of larger enterprises. This focus underscores a significant gap in understanding AM adoption in SMEs. A consensus among recent studies

---

[*] Corresponding author.
E-mail address: mathias.saterbo@uit.no (M. Sæterbø).

https://doi.org/10.1016/j.jmapro.2024.07.074
Received 10 January 2024; Received in revised form 25 May 2024; Accepted 20 July 2024

Table 1
SMEs category [15].

Company	Staff	Turnover	Balance sheet total
Small	< 50	≤ 10 million	≤ 10 million
Medium	< 250	≤ 50 million	≤ 43 million

also emphasizes the pressing need for strategies and solutions tailored specially for SMEs, and advocates for more research in the field [8,9,13]. An essential aspect is the technical attributes of various MAM methodologies and their alignment with the unique contexts of SMEs. The rapid development of MAM technologies calls for an in-depth understanding of their technical aspects. A recent study underscores this, emphasizing that despite the vast potential of MAM, industries often grapple with challenges in adopting them due to an insignificant understanding of the processes, challenges, and application-specific nuances [14]. This observation stresses the urgency of exploring these technical attributes in relation to SMEs.

This paper addresses the identified research gap by undertaking a detailed analysis of various MAM processes in the context of SMEs. The study aims to elucidate a comprehensive understanding of these processes, considering the distinctive operational and strategic needs of SMEs. It explores the compatibility of MAM technologies with the characteristics of SMEs, delineates specific challenges and opportunities inherent in adopting MAM, and formulates practical recommendations for their effective integration. The objective is to equip SMEs with essential insights to optimally leverage MAM technologies within their unique business landscapes.

The rest of this paper is structured as follows. Section 2 provides a background study, outlining the defining characteristics of SMEs. This section also sheds light on the unique challenges SMEs encounter in adopting MAM, along with a review of the current research landscape. Section 3 offers an in-depth analysis of various MAM processes, focusing on their technical attributes and industrial readiness. Section 4 discusses how these MAM processes align with the specific contexts of SMEs, culminating in the development of an evaluation matrix to guide SMEs in selecting appropriate MAM technologies. The paper concludes with Section 5, which summarizes the key findings and suggests avenues for future research.

2. Background

2.1. Definitions and importance of SMEs

SMEs are the backbone of the global economy, characterized by their size, agility, and innovative potential. Definitions of SMEs vary by country and region, often based on the number of employees, annual revenue, or assets. For instance, the European Commission categorizes SMEs based on such quantitative metrics [Table 1]. Despite these variations, the role of SMEs as catalysts of economic progress is universally recognized.

The agility of SMEs enables quicker adaptation to changing market conditions. This nimbleness is often rooted in their distinct and less complex organizational structures, which can enable faster decision-making processes, as there are fewer layers of bureaucracy. Most SMEs tend to follow a short-term strategic focus, which often limits their ability to make significant long-term investments [16]. This approach is partly due to their typically leaner operational structures, which lack expert support functions found in larger firms, such as dedicated supply chain managers, IT specialists, or financial managers [16]. Additionally, SMEs may face difficulties in accessing capital and financing, crucial for investing in advanced technologies and training. Consequently, SMEs often experience lower productivity and higher operational costs, with challenges in maintaining on-time delivery performance.

However, the size of SMEs also brings distinct advantages. Their smaller scale allows for greater flexibility and responsiveness to market changes. This adaptability is not just limited to operational agility; it often extends to their innovative capacities. SMEs can quickly pivot and experiment with new ideas, leading to the development of unique products, services, and business models. This innovative spirit is essential in driving industry advancements and can sometimes result in disruptive market changes. By focusing on niche markets or specialized customer segments, SMEs are able to offer tailored solutions that larger firms may not be able to provide as effectively. This ability to cater to specific needs and preferences can be a significant competitive edge in the fast-paced business environment.

Table 2
Characteristics of small and medium enterprises (SMEs).

Characteristic	Description
Limited Resources	Limited financial and technological resources can pose challenges in large-scale technology adoption [17].
Skilled Workforce	Often lacks specialized workforce due to broader responsibilities and lack of exposure to advanced training and mentoring.[17]. E.g., deficiency in technical expertise, or expert support roles such as supply chain managers, IT specialists, and financial managers [16]
External Networks	Less associations with universities or other research institutions as compared to larger firms [18], limiting their access to shared knowledge and cutting-edge research.
Size and Scaling Capabilities	SMEs' smaller size influences their ability to achieve economies of scale [17] and presents challenges in scaling up production efficiently. Often faces constraints in expanding production capacity due to financial, resource, and operational limitations.
Risk Aversion	Smaller scale and limited resources may lead to higher risk aversion, impacting decisions to adopt new and potentially costly technologies [19][20].
Agility in Market Response	Less complicated and more informal organizational structure [21], coupled with a less hierarchical nature [22], allows for quicker decision-making and adaptation to market changes.
Niche Market Focus	SMEs are particularly effective in adapting their offerings to meet the needs of specific consumer segments [23], advantageous for understanding specific customer needs and preferences
Innovation Potential	Strong entrepreneurial spirit, alongside less hierarchical structures [22], fostering a culture of creativity, which enhances their potential for innovation, including the exploration and adoption of new technologies
Customization Capabilities	More flexible in their production processes, likely to engage in customized, small-scale production (small batches of customized products).

The agility and innovative capacity of SMEs significantly contribute to their adaptive and competitive capabilities in dynamic market environments. However, a nuanced understanding of their intrinsic characteristics is imperative for comprehensively assessing their engagement with advanced technological paradigms such as MAM. Table 2 systematically enumerates these characteristics, delineating the operational and strategic contours that define SMEs.

2.2. SMEs and MAM adoption

MAM adoption by SMEs is complex, underscored by unique challenges and opportunities. As Mellor et al. highlights, the strategies and theories effective in large corporations might not be directly applicable to SMEs [10]. This is attributed to the distinct characteristics intrinsic to SMEs, such as their limited scale, resource constraints, division of labor, and bureaucracy [8], which influence their approach to technology adoption differently than larger enterprises. Further emphasizing this point, Martinsuo et al. articulate that grasping the specific features of SMEs is crucial for comprehensively understanding and supporting their adoption of AM technologies [8].

2.2.1. Challenges towards MAM adoption

Martinsuo et al. [8] shed light on a range of challenges faced by SMEs in adopting AM within different supply chain positions. Categorized into technological, strategic, supply chain-related, operational, organizational, and external factors, based on a generalized implementation framework previously developed by Mellor et al. [10]. These challenges include material and quality concerns, long production times, and size limitations, coupled with the absence of effective cost calculation models. Strategic hurdles such as lack of a comprehensive AM strategy and investment payback concerns pose significant barriers. Organizational and supply chain challenges, particularly in digital data integration and acquiring adequate AM knowledge. Building on the above discussion, the study by Praveen et al. [24] offers an expanded perspective on both the challenges and benefits of MAM adoption in SMEs. This research emphasizes the need for a deeper understanding of business factors, such as supply chain management and cost–benefit analysis, within the SME context. However, it also primarily focuses on the broader organizational and economic aspects of AM adoption, without delving into the specific technicalities of MAM.

2.2.2. Empirical insights and case studies

Beyond the broader theoretical discussions, there are several empirical studies and case studies that provide practical insights into the realities of MAM adoption in SMEs. For instance, Research by Deradjat et al. [11], while including both large enterprises and SMEs, offers valuable insights into SMEs' perspectives. They examine the experiences of firms in the dental sector. They reveal that SMEs often rely on external collaborations, such as government-funded research projects and partnerships with academic institutions, to overcome technical challenges in AM adoption. These collaborations are vital for SMEs to scale up their AM capabilities. In line with the need for external collaboration, as highlighted by Deradjat et al. [11], Haug et al. [9] provide a comprehensive analysis of how SMEs can leverage external networks to overcome the knowledge-related challenges in adopting AM. Haug et al. [9] emphasize the importance of SMEs leveraging external networks to overcome knowledge-related challenges in adopting AM. Building relationships with AM developers, suppliers, and organizations is crucial for enhancing internal AM maturity, especially for SMEs limited in terms of in-house expertise and resources.

José González et al. [13] present a case study focusing on the adoption of digital supply chains in AM for spare parts manufacturing. Their research highlights the benefits of adopting digital supply chains for spare parts manufacturing in SMEs. This approach can lead to significant benefits for global SMEs, including more effective logistic management and environmental sustainability.

Shah et al. [25] further enrich our understanding of MAM adoption in SMEs with their multiple case study approach. Their research provides critical insights into the actual application of AM in SMEs, the barriers to implementation, and the strategic innovations adopted. The study identifies three main challenges in AM implementation for SMEs: high entry costs, the need for customer education, and the acquisition of essential skills in design and machine handling. The insights from Shah et al. provide a practical perspective on AM adoption in SMEs, complementing the broader discussions on challenges and benefits. They further illustrate the critical role of strategic planning, organizational adaptation, and technological innovation in leveraging AM technologies for SMEs.

2.3. Decision-support systems for AM technology selection

The selection of new technology is one of the most important activities in many companies [26]. The rapid growth and development of AM have made technology selection increasingly important [27]. Although no works specifically focus on the technology selection of AM for SMEs, several studies have developed decision support systems to assist in the selection of AM technologies. These studies, while not directly targeted at SMEs, offer valuable insights into the technological landscape of AM, which is crucial for companies of all sizes.

Niaki et al. [27] summarized the state of technology selection through a comprehensive review in 2017, identifying 10 articles that evaluated AM across various selection criteria. These 10 articles used various decision-making approaches and selection criteria for identifying the best AM processes under different circumstances. However, AM technology is rapidly evolving, and many conclusions from earlier studies may no longer be relevant. For instance, Panda et al. [28] concluded that SLS was the most appropriate rapid prototyping (RP) system for better dimensional accuracy and surface quality. However, advancements in printer technology and the introduction of new systems have significantly changed the landscape. Additionally, process optimizations have been researched extensively, further altering the relevance of past conclusions.

In recent years, several studies have advanced the understanding of technology selection for AM. These works provide more relevant insights into the current state of technology. Table 3 provides a comparative overview of recent decision support systems for AM technology selection.

Most of these works either focus on polymers or provide generalized frameworks without detailed evaluations of materials or processes. For example, Maranha et al. [29] evaluate various AM processes (excluding DED) with a focus on polymers, and Ahmed et al. [30] target niche processes related to microfabrication. Both offer some practical insights but lack focus on MAM characteristics. Moreover, many studies offer decision-making tools without providing direct recommendations for specific AM processes for particular applications or business contexts. These frameworks often outline steps for selecting materials from broad categories like polymers or metals without offering concrete insights into specific products, parts, or materials. This generalized approach limits practical applicability and requires users to have prior knowledge of existing processes. Although one work [31] aims at non-expert AM adopters, the complex nature of MAM processes still demands a thorough understanding of product requirements, application areas, and broader supply chain impacts, which can limit its effectiveness.

Only two studies, such as those by Caldera et al. [26] and Bertolini et al. [32] focus specifically on MAM processes and provide more concrete insights in this area. These works are crucial as they fill a significant gap in the literature by addressing the specific needs of MAM technology selection. Bertolini et al. [32] developed a TOPSIS-based multi-criteria decision-making model to select the best manufacturing technology matching product specifications. While the study includes MAM it primarily addresses general manufacturing technologies and is validated through a case study in the food and beverage industry. This generalized framework, designed for broad applicability, lacks the depth and specificity needed for detailed insights into MAM. Additionally, the industry-specific focus and limited empirical data on MAM reduce its direct relevance to other sectors within manufacturing, where more tailored decision-making frameworks are required.

Caldera et al.'s [26] work stands out as being more directly comparable to our research. They developed a decision support framework to align AM technology characteristics with competitive criteria, providing tailored recommendations for production systems. Although they did not solely focus on MAM, they included insights on several AM processes with a metal focus. While comprehensive, the framework has its limitations. Notably, it did not cover binder jetting of metals and had a narrow set of selection criteria focusing on quality, flexibility, velocity, and cost, which may limit its applicability for broader or more specific industrial contexts. Among the future research directions suggested by the authors, there should be a more detailed quantification of certain key criteria, expanding the weight given to these criteria to enhance the accuracy and understanding of technology selection. Moreover, additional competitive and selection criteria should be analyzed, broadening the understanding of AM technology selection in various production systems and tradeoff scenarios.

Table 3

Comparative overview of decision support systems for AM technology selection.

Ref	Methodology	AM Processes	Materials Evaluated	Evaluation Criteria	Findings and Limitations
[26]	Analytic Hierarchy Process (AHP), Conjoint Analysis	BJ, LENS, FDM, MJ, EBM, SLS, SLM, LOM, SLA	Various (metal and polymer)	Cost, Flexibility, Quality, Velocity	Decision support framework emphasizing the importance of customizing AM process selection. Limited focus on metal BJ; lacks detailed tech specifications of materials; limited to four main criteria without in-depth analysis.
[33]	Rule-based decision support system, SQL database	Various 3D printing methods including FDM	General categories	Material type, layer thickness, accuracy, speed, quality, cost	Decision support system that selects the best 3D printing method based on material characteristics and quality requirements. Lacks detailed analysis of specific AM technologies and their applicability; broad approach may not address specific industry needs.
[34]	MCDM using AHP	Comparison between AM and traditional manufacturing	General categories	Economic KPIs, Environmental KPIs	AM offers environmental benefits; limited economic competitiveness compared to traditional manufacturing. Focuses on broad comparison between AM and traditional manufacturing.
[32]	TOPSIS	DMLS, SLA, Cold Metal Molding, Laser Cutting, WEDM	Metals and Polymers	Product quality, production time, costs, tolerances, lead times	Cold Metal Molding, Laser Cutting, and WEDM are the most suitable (case study). Focuses on a single case study in the food and beverage industry; limited generalizability.
[29]	Decision support system	MEX, VAT, PBF, MJ, BJ	Polymers	Machine characteristics, process features, costs	Decision support framework for AM technology selection. Focuses on polymer; generalized with limited applicability to specific use cases; lacks comprehensive quantitative data or empirical evaluations.
[35]	Hybrid MCDM, sensitivity analysis	MEX, VAT, PBF, MJ	Polymers	Dimensional accuracy, surface roughness, tensile strength, process cost, build time	MJ ranked highest for dimensional accuracy and surface quality; Generalized framework with limited applicability to specific use cases; limited quantitative data and empirical evaluations; focuses on polymers.
[30]	Fuzzy AHP – TOPSIS	LIFT, Micro-SLA, Micro-SLS, Inkjet, Micro-3D Printing	General categories	Material Compatibility, Geometrical Complexity, Minimum Feature Size	LIFT ranked highest; Focuses on microfabrication, limiting relevance to general industrial applications.
[31]	Multi-level evaluation framework	Various	General categories	Geometry, Material, Lot size, Lead time, Unit cost	Three-level framework for evaluating AM applicability and planning hybrid manufacturing processes. Generalized framework with no in-depth information on specific AM processes.
[36]	AHP, TOPSIS	Not specified	General categories	Surface finish, Dimensional accuracy, Tensile strength, Cost, Time	Hybrid MCDM framework; case study validation. Generalized framework; lacks detailed process evaluation.
[37]	DEMATEL-AHP-TOPSIS	ME, PBF	Polymers (ABS, PLA, PA)	Tensile strength, Dimensional accuracy, Surface finish, Cost, Biocompatibility	DSS with minimal user input; supports DFAM; validated by case study. Focuses on polymers and evaluates only ME and PBF; lacks specific recommendations for process suitability.

2.4. Reserach gap

From the existing literature, a key area remains notably underexplored: the in-depth technical analysis of MAM processes. This oversight is significant given the intricate technicality of MAM and its potential implications for SME operations.

The need for this detailed analysis is threefold. Firstly, understanding how MAM integrates into SMEs' distinct operational frameworks is vital, as these frameworks often have unique limitations and strengths. Secondly, a technical analysis can offer insights into the practicality of different MAM technologies for SMEs, considering their specific needs such as resource constraints, production scale, and customization requirements. Finally, it can highlight areas where technical training and development within SMEs are needed, ensuring the effective maximization of MAM benefits.

While several studies have touched upon this aspect, they have not delved deeply into it. For instance, Deradjat [11] criticizes the generalized approach of existing frameworks, calling for more attention to technical factors. This is further evident in the current overview of decision support systems for AM technology selection. Among all the works, only a handful provide concrete practical insights, and for MAM, only two studies have been conducted. Still, these studies either focus on a niche application sectors or lack detailed criteria for evaluation and quantification. Caldera et al. [26] emphasize the need for more criteria evaluation and detailed technical factors, underscoring the need for comprehensive technical analysis.

Based on these elements, it is essential to broaden the technological knowledge of MAM among SMEs. This need is also highlighted in other studies. Shah et al. [25] point out the gap in understanding the interplay between organizational and technological factors, while Valadar et al. [14] emphasize the need for robust knowledge of MAM processes, particularly the challenges and application-specific requirements crucial for SMEs. Addressing this gap is essential, not just for theoretical comprehension but also for practical applications, particularly in the context of the fast-evolving nature of MAM technologies and the diverse operational environments of SMEs.

3. Metal additive manufacturing

MAM has evolved rapidly since its inception in the 1990s, transitioning from a tool for rapid prototyping to a mature manufacturing technology for end-use parts. This evolution is well-documented in the literature [38,39], which details the historical development and market dynamics of MAM, highlighting significant technological advances over recent decades and future prospects. The rich history and varied applications of MAM necessitate an in-depth understanding of its current technologies, focusing on their capabilities, advantages, and challenges amidst ongoing advancements and the diversity of processes tailored for specific needs.

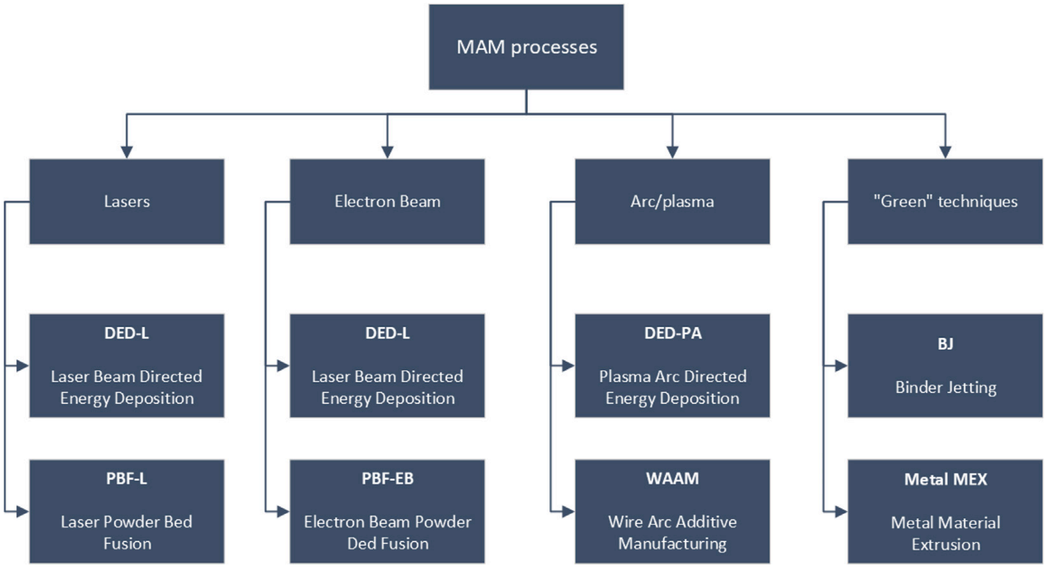


Fig. 1. MAM process overview according to ASTM standard [1].

3.1. Process overview - MAM

The ISO/ASTM 52900 [1] standard provides a widely recognized framework, categorizing MAM into seven principal categories: Powder Bed Fusion (PBF), Material Jetting (MJ), Material Extrusion (MEX), Directed Energy Deposition (DED), Binder Jetting (BJ), Sheet Lamination (SL), and Vat Polymerization. Each of these categories is distinct in terms of the materials used, bonding mechanisms, fusion processes, and their respective advantages and challenges. Given the diverse array of MAM technologies, our focus narrows to the processes that are at the forefront of industrial adoption and technological advancement. These include PBF, DED, BJ, and MEX. Fig. 1 illustrates the most common techniques for these four processes according to the energy source. Furthermore, Table 4 summarizes the basic process nature of these four MAM processes.

- **PBF**: Involves selective melting/partial melting and solidification of a powder material layer by layer using a focused energy source, typically a laser or electron beam [40]. Mainly 3 variants exist based on energy source and powder particle fusing mechanisms, including SLS, SLM, and EBM [41]. PBF requires controlled atmospheric conditions and precise parameter control for efficient production [42–44].
- **DED**: Functions by layer-by-layer metal deposition using focused thermal energy, such as a laser or electron beam, to melt materials during deposition [45]. Several process variations exist based on their energy source, Plasma/ARC (WAAM), laser (LMD, WLAM), and electron beam (EBAM) [46]. DED is known for its capability to deposit large volumes and uses both powder and wire feedstock. Operational efficiency in DED depends on careful management of deposition parameters and cooling rates [47].
- **Metal MEX**: In Metal MEX, a blend of metal powder and polymeric binders is extruded layer by layer. The process includes extruding the ‘green’ part, debinding to eliminate binders, and a sintering phase for part densification [48]. Technical challenges involve managing the composite feedstock and precision in the debinding and sintering stages.
- **BJ**: Utilizes a liquid binding agent dispensed onto layers of powder, followed by sintering [49]. The process requires optimization in printing and post-processing methods, with a focus on managing powder deposition, binder/powder interaction, and curing [50].

3.2. Comparative description of MAM processes

As MAM solidifies its role across various industrial sectors, synthesizing existing knowledge about its processes becomes increasingly important. Numerous studies have outlined the advantages and disadvantages of different MAM techniques. In response to recent advancements and evolving market demands, we have consolidated these insights and presents a comparative summary of these techniques, offering a detailed perspective that assists in discerning the most suitable MAM techniques for specific industrial applications.

3.2.1. Market presence and technological maturity

Understanding the market presence of each MAM process provides insights into their adoption, industry prevalence, and current trends. Fig. 2 illustrates the market share of each MAM process in 2019 [51].

- PBF: Dominating the MAM market, PBF is particularly favored in precision-demanding industries like aerospace, medical, and automotive [42]. Its ability to produce high-quality, dense metal parts is a key factor in its market leadership, as highlighted in the AM Power report [51].
- DED: Despite a smaller market share (8% in 2019), DED is vital for niche applications such as repair and large-scale part production, offering unique value in sectors that require material addition to existing components [45].
- MEX, BJ, and SL: Collectively, these processes accounted for about 7% of the MAM market in 2019. MEX, attracting attention for its simplicity and cost-effectiveness, is increasingly popular in sectors seeking accessible MAM solutions [48]. BJ is gaining traction due to its versatility and efficiency in a wide range of applications [50].

In terms of technological maturity, Laser Powder Bed Fusion (L-PBF), a variant of PBF, exemplifies the advanced development stage of MAM technologies. DED is also recognized for its industrial readiness, catering to diverse applications such as repair and large part manufacturing [47]. The AM Maturity Index from AM Power indicates that currently, only a few MAM techniques, mainly types of DED and PBF, are considered industrially viable [52]. However, with BJ and MEX approaching this readiness stage, there is an anticipated shift in the market and technology landscape. This shift is expected to see a rise in the market shares of DED, MEX, and BJ in the coming years, reflecting the evolving dynamics in MAM.

Table 4
MAM process nature.

	Basic Principle	Processes	Material type	Applications	Ref
PBF	Thermal energy selectively fuses metal powders laid out on a powder bed	SLS/DMLS SLM/LBPF EBM	Powders	Functional metal parts, functional prototyping	[40]
DED	High-energy heat source (laser or electron beam) melts metal feedstock during deposition to build a part layer by layer	LMD, LENS, WAAM, WLAM EBAM	Powders or wire	Functional metal parts, repairs, adding material to existing parts	[45][47]
BJ	A liquid binding agent is selectively deposited to join powder particles	Metal Binder jetting	Powder and polymeric binders	Functional metal parts, low-rate production runs of non-critical	[50]
MEX	Heated filament or feedstock of metal powder and binder composite extruded through a nozzle	Metal MEX (Screw-based, Plunger-based, Filament-based)	Powder with binder material	Functional metal parts, prototyping	[48]

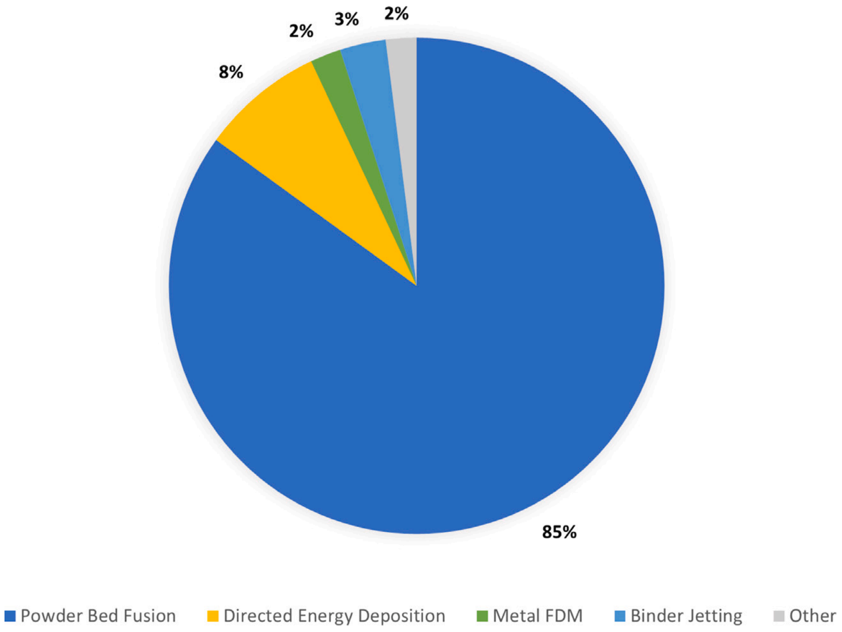


Fig. 2. Market overview MAM - 2019 [51].

3.2.2. Technical overview

Each MAM process exhibits a unique set of technical attributes that determine its effectiveness and suitability for specific manufacturing applications. The existing literature provides an overview of these attributes. Tables 5 and 6 offers a synthesized comparative overview of the technical aspects of four key MAM processes.

Quality is a critical characteristic for adopters and can be primarily divided into mechanical and geometrical requirements [53]. Mechanical requirements typically include strength, elasticity (Young's modulus), toughness, fatigue, and hardness. Table 5 provides an overview of the strength and elasticity, specifically for stainless steel 17-4 PH in the horizontal orientation, as reviewed by Armstrong et al. [41]. The reported values represent averages derived from multiple studies included in the review and can vary significantly based on factors such as the specific printer, material, and process settings. Baseline values for wrought, metal injection molding (MIM), and casting processes are also provided for comparison. Geometrical requirements include surface roughness, dimensional accuracy, and geometrical tolerances as defined by ISO standards, illustrated in Table 6. The geometrical accuracy of Directed Energy Deposition (DED) and Material Extrusion (MME) is derived from specific studies and can vary considerably based on factors such as printer setup, material used, and process parameters [53,54]. Generally, a thinner layer thickness during MAM can lead to higher accuracy, better surface quality, and densification [55], though at the cost of build speed. For example, Manuela et al. [54] report major differences in surface finish for MME when varying layer thickness.

In addition to quality attributes, other important technical factors include energy consumption, costs, and production speed. The cost of MAM solutions varies widely due to the diverse sizes and capacities of printers. Most suppliers do not publicly disclose their pricing; however, general trends in costs can be inferred from industry reviews such as Khorsani's analysis of PBF systems [42] and comprehensive lists of MAM solutions [56,57]. The cost range specified in the table reflects the spectrum of costs for different processes, with PBF and DED typically being more expensive, followed by BJ and MME as the most cost-efficient system. Finally, the production speed and deposition rates vary significantly depending on the process parameters used in the experiments. While a thinner layer thickness during MAM can improve accuracy and surface quality, it typically reduces build speed.

Comparing different MAM processes directly presents inherent challenges due to their distinct operating principles. For instance, BJ utilizes binder extrusion, MEX fuses powder with a binder, DED employs wire or powder extrusion, and PBF uses a laser or electron beam for material fusion at a powder bed. These fundamental differences in thermal sources, consolidation mechanisms, and feedstock forms necessitate that each process be evaluated on its unique merits. Recognizing this, the technical overview is further complemented by a detailed analysis

Table 5
Mechanical properties (average values) of 17-4 PH stainless steel for PBF, DED, BJ and MEX adopted from [41].

Process	Orientation	UTS (MPa)	YS (MPa)	Elong. (%)
PBF	Horizontal	1257	1088.3	13.9
DED	–	1134	1053	7.6
BJ	Horizontal	1077	885.2	8.2
MEX	Horizontal	1046	730	6.75
Wrought	–	1379	1233.5	15
Casting	–	1306	1161	4.35
MIM	–	862.5	852.5	6

in Tables 7–10. These tables delve into the specific strengths and challenges of each MAM process, as identified in the existing literature. It offers a in-depth view that assists in determining the optimal suitability of each process for various applications. This approach underscores that while every MAM process has distinct advantages, they also possess particular limitations, rendering them more appropriate for certain manufacturing scenarios than others. This nuanced understanding is crucial for appreciating the diversity and potential of these processes in various industrial contexts.

3.3. Comparative analysis

This study evaluates the performance of PBF, DED, BJ and MEX by quantifying and scoring eight key criteria: cost, complexity, energy consumption, production speed, market demand, surface roughness, dimensional accuracy, and quality. However, comparing the MAM processes is no easy feat due to the differences between processes and the inherent uncertainty and various ranges in the data. Thus to navigate these challenges we adapted a fuzzy logic approach as outlined by Chan et al. [84]. Furthermore, we employed logarithmic normalization to manage a wide range of values and scaling to ensure comparability.

The criteria were first classified into objective and subjective categories.

- **Objective criterias:** Cost, energy consumption, production speed, mechanical quality, surface roughness, dimensional accuracy, and market demand
- **Subjective criterias:** Complexity

Data for each criterion were collected from established literature and technical specifications as summarized in the tables above. Numerical values were gathered for objective criteria, while linguistic evaluations were used for subjective criteria. To handle the inherent variability and uncertainty in the data, we converted the collected data into Triangular Fuzzy Numbers (TFNs). TFNs provide a way to represent data with three parameters: minimum, average, and maximum values. The linguistic variables used for subjective criteria were converted into TFNs using predefined scales. The linguistic scale was defined as follows:

- Low (L): (1,1,2)
- Medium (M): (1,2,3)
- High (H): (2,3,3)

For the subjective criterion of complexity, several subcategories were evaluated to understand the overall complexity of each MAM process. These subcategories included material handling, energy source, inert atmosphere control, software, and monitoring. Each subcategory was assessed using the defined linguistic scale (L, M, H). The evaluations for each MAM process were converted into TFNs, and the average fuzzy number for each technology was calculated. The evaluations for the complexity criterion are summarized in Table 11.

Next, we conducted fuzzy set analysis to process the TFNs. This involved aggregating the TFNs for each criterion across different technologies and normalizing the fuzzy sets to ensure comparability. Defuzzification was performed to convert the fuzzy values into crisp scores using the center of gravity method, providing a clear quantitative measure for each criterion. Given the wide range of values across the different criteria, logarithmic normalization was employed to handle these variations and make the data comparable. This process included converting each value to its logarithmic equivalent to handle large disparities in magnitude and normalizing these logarithmic values based on the observed minimum and maximum values.

The scaled scores for all criteria were then combined to derive a score for each technology. This was done by averaging the scaled scores for each criterion, ensuring that each criterion was equally weighted in the final evaluation, providing a balanced assessment of the overall performance of each MAM process. Fig. 3 illustrates the relative performance of each process across these key areas. This radar diagram offers a clear and concise comparative perspective, highlighting the strengths and weaknesses of each MAM process. While the analysis is partly subjective, it is grounded in the available literature and effectively illustrates the diverse capabilities of these technologies.

- **PBF:** Exhibits high geometrical and mechanical quality, making it feasible for high-end markets with strict mechanical and geometrical requirements. However, it faces significant challenges in cost efficiency and ease of integration due to high initial investments and the need for specialized expertise.
- **DED:** Offers moderate production speed and material flexibility, suitable for large-scale parts manufacturing and repair. It is constrained by high operational complexity and safety concerns, requiring precise control and monitoring, which can be a barrier for SMEs with limited technical expertise.
- **BJ:** Provides moderate cost efficiency and high production speed. It has moderate complexity but faces challenges related to part quality and surface roughness, necessitating careful consideration of quality trade-offs. Its lower entry costs make it attractive for SMEs focused on fast production.
- **MEX:** Stands out for its affordability and simplicity, making it ideal for SMEs focusing on prototyping and low-volume production. However, its slower production speed and moderate part quality can limit its applicability for high-volume or high-precision manufacturing.

4. Discussion of MAM in the context with SMEs

The comparative analysis presented in Tables 6–10 and Fig. 3 elucidates the distinct advantages and challenges inherent in each MAM process. This understanding is particularly important when considering the integration of these processes within varied manufacturing environments, such as those faced by SMEs. Translating these technical details into actionable strategies is imperative for strategic decision-making in SMEs. it is crucial to recognize that the decision to adopt a particular MAM process transcends mere technological capabilities. It encompasses a broader consideration of how these technologies align with the specific operational, financial, and strategic requisites of SMEs. They must consider factors such as required investment, the complexity of operations, the quality, and demands of their market, and their capacity for in-house expertise development.

4.1. Implementation of PBF in SMEs

4.1.1. Financial barriers

PBF, with its capacity for producing high-precision and detailed parts, presents both opportunities and challenges for SMEs. Perhaps most notable is the high capital costs, being the most expensive among the various MAM processes, which may pose a significant barrier for SMEs with limited investment capabilities. The costs associated with acquiring a PBF machine, along with the necessary ancillary equipment and materials like specialized powders, are substantial. Given the substantial costs associated with PBF, effective cost-reduction strategies

Table 6
Comparison of metal additive manufacturing processes.

Attribute	L-PBF	L-DED	MEX	BJ
Deposition rate	0.1–0.18 kg/h [46]	0.1–1.41 kg/h [46]	5–15 mm/s [58] Up to 80 mm/s [48]	Up to 200 cm^3/min [59]
SEC (kWh/kg)	31.11–155.17 [41]	5.18–292.22 [41]	33.19 (printing only) [41]	2.47 (printing only) [41]
Surface Roughness (μm)	16–35 [60]	25–35 [61]	9.56–18.10 [62]	0.5–50 [55] Avg: 12.84 [63]
Accuracy	±0.1 mm [64] ±0.12 mm [65]	±0.34 mm [53]	±0.25 mm [54]	±0.3 mm ±0.5 mm [50]
Capital Costs	$90k–$2 m [42,56]	$90k–$210k (WAAM) [66] $150k–$2 m [57]	$10k–$135k [56]	$150k–$400k [56]

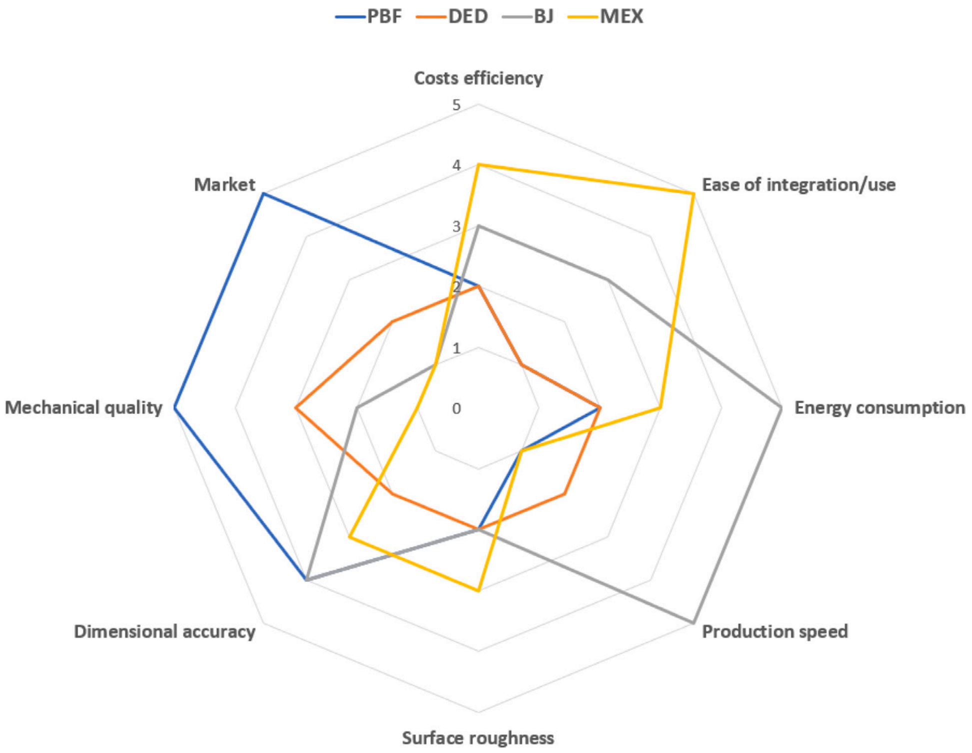


Fig. 3. Comparison between the different MAM processes.

Table 7
Advantages and limitations of PBF according to existing literature.

Advantage	Limitation
• Produces parts with excellent mechanical properties, including high precision [67], and high specific strength and stiffness [68] • Enables efficient use of materials through recycling [67] and near net-shaped production [41,69,70]. • Capable of producing fully dense parts [71]. • Wide selection of materials [41].	• Necessitates support structures and post-processing, such as build plate separation and finishing [41,67,72]. • Limited by the size of the build chamber and powder bed [67]. • High residual stresses due to thermal influences [72]. • Health and safety concerns due to the use of fine powders and lasers [67]. • Surface finish may exhibit "stair stepping," generally requiring additional post-process smoothing [67]. • Slower production speeds [67,73]. • Operation complexity demands skilled operators and meticulous process control [69]. E.g., in modern L-PBF systems there are more than 100 processing parameters [72].

Table 8
Advantages and limitations of DED according to existing literature.

Advantage	Limitation
• Offers versatility with a large build area [74]. • Accommodates a diverse array of materials, facilitating wide application use [47,74]. • High deposition rates [41,75]. • Ideal for depositing material to an existing surface, beneficial in repair and manufacturing hybrid structures [41,76]. • Can change the deposited material directly during the manufacturing process [75,76]. • Support structure typically not needed [77]	• Substantial post-processing to refine the surface finish and dimensional accuracy [47]. • Poor surface finish [75]. • The thermal nature of the process can introduce residual stresses, potentially necessitating additional treatments [47,78]. • Health and safety concerns due to high-energy beam usage [79].

become crucial for SMEs. The primary scenario where PBF becomes cost-competitive is in the production of small, specialized high-value components that require intricate designs and high precision. This aligns excellently with DFAM practices. The high expenses, predominantly driven by machine and material costs [85] can be substantially mitigated through Design for Additive Manufacturing (DFAM). DFAM can lead to significant cost reductions — up to 70% in production

Table 9
Advantages and limitations of MEX according to existing literature.

Advantage	Limitation
• Recognized for its cost-effectiveness accessibility, being 60%–80% cheaper than PBF [80]. • Low barriers to usage because of its ease of use and similarity to widely known FDM process [81]. • Demonstrates efficient material utilization by depositing where needed, minimizing waste. • Relatively safe and clean operational processes [48]. • Yields relatively high accuracy in part fabrication [41].	• May necessitate support structures for certain geometries such as overhangs or unsupported features [81]. • Tends to exhibit high porosity, affecting part density [41]. • Often results in a sub-optimal surface finish, suffering from the “staircase” effect [41,81]. • Post-processing, including debinding and sintering for densification, as well as support removal and machining, is essential for enhancing part quality and surface finish [41,48]. • Anisotropy is typical due to voids between layers [41].

Table 10
Advantages and limitations of BJ according to existing literature.

Advantage	Limitation
• Cost-effective for certain applications, particularly due to its relatively lower machine costs [55,82]. • Exhibits high scalability potential, making it suitable for various production volumes [82]. • No need for support structures [50,82]. • Wide range of available materials. Not affected by optical reflective, thermal conductivity, or thermal stability [82]. • Achieves relatively high production rates as only the binder is deposited [50,55]. • Good final surface finish [41].	• Characterized by low density, high porosity, and unpredictable shrinkage during post-processing [41,55,83]. • Multistep process, including debinding and sintering [55]. • Involves careful powder handling and safety precautions to mitigate risks associated with fine powders and binding agents [41].

Table 11
Complexity evaluations for MAM processes.

	PBF	DED	BJ	MEX
Material	H	M	H	L
Energy	H	H	L	L
Atmosphere	H	H	M	L
Software	H	H	H	L
Monitoring	H	H	L	L

costs and a 71% decrease in production time [86] through lightweight designs and minimization of waste and support structures.

4.1.2. Operational integration

However, such cost reduction strategies, while a necessity, add another dimension of challenges. PBF requires a specialized environment and extensive technical expertise across several domains, including material science, machine operation, DFAM, and post-processing techniques. For instance, Armstrong [41] estimates that over fifty distinct process parameters can impact the final properties of printed parts, from pre-defined, controllable, and post-processing variables [87], each requiring meticulous in-situ optimization to circumvent potential defect. This complexity translates into a steep learning curve for employees, particularly challenging for SMEs with their limited access to a specialized workforce. The high stakes of PBF in producing critical components for high-end markets amplify the necessity for stringent compliance to standards, further complicating its adoption for SMEs. The intensive expertise required for PBF operation and the critical importance of DFAM in optimizing production costs and times mean that SMEs must balance their limited resources with the need for specialized knowledge. Collaborative ventures with technical experts and academic institutions can mitigate these challenges but may incur additional costs. Such collaborations, though potentially valuable in bridging the knowledge gap, must be weighed against the resource limitations typical of SMEs.

4.1.3. Safety and compliance

Integrating PBF into SMEs not only poses financial and technical challenges but also raises significant safety concerns. PBF is among the most hazardous MAM techniques, primarily due to its use of fine metallic powders [41]. These powders present multiple risks, including respiratory hazards for operators and potential fire and explosion hazards due to their flammability. In SMEs, where experience in handling such materials safely may be limited, these risks are even more pronounced.

4.1.4. Strategic considerations

Nonetheless, PBF presents significant advantages for SMEs that can overcome the financial and technical challenges. Its unparalleled design flexibility and precision manufacturing align seamlessly with SMEs’ strengths in offering customized, high-value products. PBF is particularly well-suited for small batch sizes and low-volume production, which is often the operational scale of many SMEs. This technology excels in producing complex and high-quality parts without necessitating large-scale production runs, making it ideal for SMEs that specialize in low-volume, customized orders. Moreover, PBF’s capabilities allow SMEs to cater to niche markets and meet specific customer needs with a high level of precision and customization. Given that SMEs are typically more agile and have closer relationships with their customer base, they can leverage these aspects of PBF to rapidly deliver tailor-made solutions. This advantage is particularly potent in sectors that value intricate design and customization, offering SMEs a pathway to differentiate their products and services in competitive markets.

4.1.5. Market opportunities and Niche applications

With the technical and financial challenges, the practicality of SMEs adopting PBF is contingent on their ability to secure a market niche where such high-value components are in demand. These markets should value the unique capabilities of PBF, such as complex geometries and custom designs, enough to bear the associated costs. Industries like aerospace, medical, and automotive, which require precision parts with complex geometries, could provide viable markets for SMEs utilizing PBF. Yet, this niche application means that PBF is not suitable for all SMEs, especially those whose production needs do not align with these high-value, specialized sectors. SMEs considering PBF must therefore conduct a thorough assessment of their market strategies, target customer base, and financial capabilities. While PBF offers the potential to produce unique and complex parts, the return on investment for SMEs hinges on their ability to penetrate and serve markets where such specialized production is not just needed but also financially rewarding. This strategic alignment is critical for SMEs to justify the high initial investment, ongoing operational costs, and significant technological dive associated with PBF technology.

4.2. Implementation of DED in SMEs

4.2.1. Financial barriers

Integrating DED into SMEs presents a complex set of challenges and opportunities, primarily influenced by substantial investment and operational costs. The initial financial outlay for DED equipment often represents a significant barrier, given the limited capital availability typical of SMEs. This is compounded by ongoing operating expenses, such as maintenance, energy, and material costs, adding to the financial burden.

4.2.2. Operational integration

Operational complexity is another critical factor, especially considering the high build volumes associated with DED. Controlling the DED process is complicated, as the majority of users often rely on expensive and time-consuming techniques, such as multiple experimental runs, to define optimized process parameters [75]. Given the necessity for specialized knowledge in accurately controlling process parameters, SMEs may face hurdles due to their typically limited access to the specialized workforce due to broader responsibilities and limited exposure to advanced training and mentoring [17]. As Armstrong et al. [41] highlight, precise control over thermal power, feed rate, beam focus, and cooling cycles is crucial for maintaining part integrity and avoiding defects such as residual stresses, porosity, and cracking. Moreover, the safety hazards associated with DED, such as exposure to high-energy beams and potentially harmful fumes, exacerbate the need for specialized knowledge and skills. The risks of operating such equipment without the requisite expertise are significant, both in terms of employee safety and product quality.

4.2.3. Market opportunities and flexibility

Still, if SMEs somehow overcome these initial financial and knowledge barriers (e.g., through external collaborations or government funding incentives [8,11]), then DED can offer excellent flexibility and production rates. Its high deposition rates are making DED one of the most promising economical alternatives for manufacturing large metal parts [66]. As a rough order of magnitude: PBF processes can achieve rates of about 0.1 kg/h, whereas DED processes reach average rates of 1 kg/h, and are capable of going up to 4 kg/h [88]. This flexibility could be particularly beneficial for SMEs engaged in niche markets or specialized manufacturing sectors where such capabilities are in demand. However, this advantage should be weighed against the fact that SMEs often deal with smaller production volumes, and their market focus might not always require the unique capabilities of DED. Nonetheless, For SMEs aiming to scale up their production, especially in sectors where large components manufacturing is a norm, DED offers a viable solution. Similarly, for SMEs operating in MRO (Maintenance, Repair, and Overhaul) sectors, where DED specific ability to deposit material directly to an existing surface, differentiates it from all other processes where it is able to repair damaged components providing good mechanical properties that for the most part is comparable with bulk material [76]. This could allow these SMEs to offer specialized, high-value services that differentiate them from competitors.

4.2.4. Challenges and post processing

While DED's high deposition rates are advantageous, the requirement for extensive post-processing might not align well with the operational tempo of SMEs, especially those dealing with smaller batch sizes or custom orders. I.e., SMEs need to respond to quickly to customer demand might be offset by the extensive post-processing needs.

4.3. Implementation of BJ in SMEs

4.3.1. Cost considerations

BJ's distinct sinter-based approach contrasts sharply with the fusion-based techniques of DED and PBF. This unique nature opens up a range of opportunities for SMEs, yet also requires careful navigation of its specific challenges. The relative affordability of BJ in terms of equipment and material costs is a key advantage for budget-conscious SMEs. However, the total cost of ownership, encompassing maintenance, materials, and particularly post-processing requirements, needs thorough consideration.

4.3.2. Operational complexity and technical expertise

BJ's technical complexity is also considerably lower than that of DED and PBF, mainly because it does not involve laser or electron beam melting processes eliminating the need for precise control and management of beam parameters such as power, speed, and focus significantly reducing the technical expertise. Additionally, the sintering process in BJ is a well-understood technique in the manufacturing industry [83]. This familiarity offers an advantage to SMEs, as it aligns with existing knowledge and practices, further reducing the operational complexity. Unlike the precise and often complex thermal management needed in DED and PBF, BJ's sintering process is more straightforward, making it a less technically demanding option for SMEs.

However, despite its simpler operational complexity, a significant issue with BJ is its technical maturity. For SMEs, this lack of maturity means dealing with a technology that is still evolving and may not yet meet all industrial standards, especially in producing parts with high precision and consistency. This uncertainty can be problematic for SMEs that require reliable and stable manufacturing processes for their products. The decision to adopt BJ must be balanced against the potential risks associated with its evolving nature, which might include more frequent updates, adjustments in processes, and adapting to advancements as the technology matures. It is particularly its current limitations in part quality that cannot be overlooked. BJ typically exhibits lower surface roughness, accuracy, and resolutions [55]. Furthermore, the high porosity of BJ parts, resulting in up to 50% less density compared to PBF-produced parts [55], is a major concern, impacting the sintering process with considerable and unpredictable shrinkage. BJ's current inability to predict and control this shrinkage challenges its application in producing parts with strict tolerances required for many industrial uses [83]. This unpredictability requires SMEs, especially in high-precision sectors, to carefully assess BJ's alignment with their quality and accuracy requirements.

4.3.3. Market customization and material flexibility

However, advancements in controlling this shrinkage could greatly enhance BJ's applicability. BJ's larger material pool, absence of support structure requirements, high scalability, fast production rates, and simpler, safer operations [82] are all benefits that can offer huge potential for SMEs as the technology matures. Part of this potential comes from BJ possibility to virtually process any powder feedstock [50,55], not limited by factors like optical reflectivity or thermal conductivity that challenge DED and PBF [82]. This material flexibility aligns well with SMEs. The versatility in material selection allows SMEs to adapt swiftly and efficiently to their local customers' needs, offering tailored solutions. This attribute of BJ, being able to handle various materials, provides SMEs with the flexibility to explore and cater to diverse market demands, enhancing their competitive edge. Additionally, while BJ's rapid production speed is a notable advantage, its impact may be moderated by the necessity of post-processing [89]. For SMEs, particularly those engaged in smaller-scale operations, the high production rates of BJ might not be a primary requirement. In particular, as seen by praveen [24] Production capacity expansion did not prove to have a significant influence on AM Because SMEs already have fixed production capacity with present plant and machinery; hence, the companies might not be able to perceive AM for mass customization and enhancing the production output.

4.4. Implementation of MEX in SMEs

4.4.1. Cost efficiency and operational simplicity

Metal MEX, sharing a sinter-based approach with BJ, presents unique cost considerations for SMEs. Unlike the more advanced and costly PBF and DED methods, MEX is affordable in terms of equipment and operational expenses. This affordability is a significant advantage for budget-conscious SMEs, allowing them to integrate MAM into their processes without a substantial financial investment. The operational simplicity of MEX, akin to familiar polymer FDM/FFF techniques, reduces the learning curve for SMEs. This simplicity benefits SMEs, often lacking specialized staff, as MEX does not demand intricate control like PBF or DED. Furthermore, the safety aspects of MEX make it an appealing option for SMEs. The lack of hazardous material handling, as seen in powder-based methods, reduces safety risks and the need for complex infrastructure. However, despite these initial advantages, SMEs must also weigh the ongoing costs associated with MEX, such as maintenance and materials. Understanding MAM basics, including design principles and post-processing techniques, remains essential. The technical maturity of MEX is also a factor for SMEs. As a relatively new entrant in the MAM landscape, MEX is still evolving, which could pose challenges in consistency and quality standards expected in certain industries. Although slightly more advanced than BJ, SMEs aiming to adopt MEX must be prepared to adapt to technological advancements and updates in the process.

4.4.2. Technical maturity and part quality

In terms of part quality, MEX generally has a lower resolution compared to PBF and DED but is capable of producing functional metal parts with mediocre surface finish [41], good mechanical properties [77], and without the stresses typically seen in thermal processes. These properties depend on the material, printing parameters, and post-processing techniques. Overall, MEX can compete with other AM techniques when the feedstock is homogeneous, ensuring uniform and isotropic shrinkage [77] - a significant advantage over BJ, which currently faces challenges with unpredictable and uncontrollable shrinkage. To achieve defect-free parts with high relative sintered density, meticulous control of printing parameters is crucial (e.g., flow rate multiplier, layer thickness, and extrusion temperature) [90,91]. Non-optimized printing parameters and lack of debinding and sintering experience can adversely affect mechanical properties and part quality. However, this challenge is already addressed by user-friendly, closed MEX systems, which come as complete sets, restricting users from using third-party feedstock and varying debinding and sintering parameters [48]. Thus, MEX demonstrates its potential for SMEs by offering a balance of cost-effectiveness, simplicity, and part quality. Its ability to produce metal parts comparable in quality to more established AM processes or MIM processes [41,77]. Coupled with the relative ease of operation, positions it as a promising option for SMEs, especially those venturing into metal AM for the first time.

4.4.3. Production speed limitations

A significant limitation of MEX lies in its production speed. Typically, the printing speed for MEX is relatively low, ranging from 10–100 mm/s [58], and this is further compounded by the multi-step process involving debinding and sintering. While it is possible to increase the printing speed, this adjustment demands careful monitoring due to its substantial impact on part quality. Accelerating the process can lead to issues such as poor layer adhesion, diminished mechanical properties, and reduced precision in the final products [48]. Consequently, this limitation predominantly confines MEX to applications in prototyping and low-volume production, potentially making it less viable for SMEs engaged in high-volume manufacturing. However, for SMEs seeking a swift entry into MAM with lower production volumes and a focus on complex, customized parts, the slower speed of MEX may not be as critical. In such cases, the technology's benefits, such as cost-effectiveness and simplicity, can outweigh the limitations posed by its slower production speed.

4.4.4. Adoption strategies with MEX

SMEs must carefully evaluate their process needs. If time efficiency is crucial, printing speed can be increased, but this requires a strategic balance in printing parameters to ensure the maintenance of quality standards. Likewise, the debinding and sintering operations can be optimized. For example, there are systems available that eliminate the need for a separate debinding step [92], and sintering setups can be tailored based on production volume and specific needs. In industrial settings, continuous sintering is recommended for economical production, whereas for batch production, parts are typically placed on ceramic trays in the sintering furnace [77].

4.5. SME-focused evaluation matrix

It is clear the four MAM processes of PBF, DED, BJ, and MEX, each offer distinct advantages and challenges for SMEs. In choosing the most suitable MAM process, SMEs must carefully evaluate these processes against their specific needs, market demands, and resource availability. The decision depends heavily on the unique context of each SME. While PBF and DED might be more suited for SMEs targeting high-end markets with complex part requirements, MEX and BJ could be more appropriate for those seeking cost-effective solutions for customized, low-volume production.

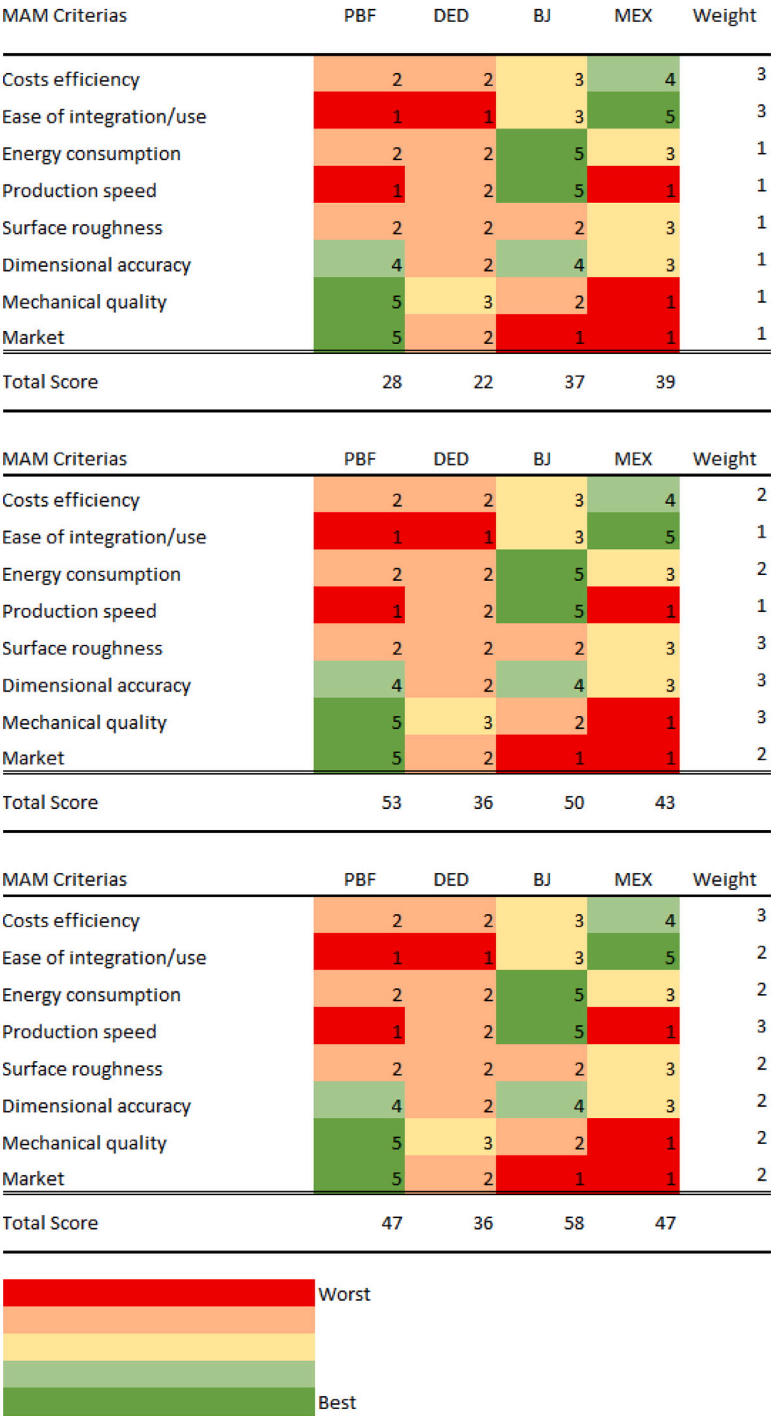
To facilitate this decision-making process, we illustrate an evaluation matrix that compares MAM processes against the mentioned criteria important to SMEs. This matrix is based on the radar diagram in Fig. 3 and serves as a guide, encouraging SMEs to conduct a thorough and nuanced assessment of each MAM process. The importance of each criterion can vary significantly between different businesses, sectors, and market demands, underscoring the necessity of a tailored analysis for the effective adoption and integration of MAM. Fig. 4 illustrates three practical applications/examples of the evaluation for SMEs with different focuses:

Cost and complexity focus: For SMEs venturing into MAM for the first time, minimizing cost and complexity is often crucial due to limited budgets and resources. These businesses frequently target the low-end market, where affordability and straightforward integration are paramount. BJ and MEX score higher in this context because of their cost efficiency and straightforward operation. BJ is relatively affordable in terms of equipment costs, and its operational complexity is lower compared to PBF and DED. MEX stands out for its affordability and simplicity, aligning well with SMEs that have limited resources and are looking for an accessible entry point into the MAM market. However, MEX comes with challenges related to part quality and production speed, which SMEs must consider.

High-Quality and Precision Focus: For SMEs targeting markets that require high precision and strict tolerances, PBF is the most suitable option. PBF excels in producing high-precision, detailed components, making it ideal for specialized, high-value applications. Its high cost and technical complexity can be justified in markets such as aerospace and medical devices, where precision and quality are paramount. SMEs need to weigh these benefits against the significant investment and operational expertise required to effectively utilize PBF technology.

Volume and Speed Focus: For SMEs that prioritize production speed and volume, BJ stands out due to its high production speed. BJ's ability to produce parts quickly makes it ideal for SMEs focusing on rapid manufacturing and high throughput. Although its part quality may not match that of PBF or DED, the trade-off in speed and cost efficiency can be beneficial for SMEs in industries where quick turnaround times are critical. MEX also performs well in terms of cost-effectiveness and simplicity, but its slower production speed limits its applicability for high-volume manufacturing.

These examples demonstrate how the evaluation matrix can be adapted to different SME priorities. The scenarios underscore that the optimal MAM process is not a one-size-fits-all solution and must be tailored to the specific needs of each SME. While MEX offers compelling benefits for SMEs just venturing towards MAM, there may be instances where an alternative process is more appropriate. Herein, the overarching theme is clear: the successful integration of MAM technologies within SME operations hinges on a tailored approach. This paper has delved into the technical aspects of the most industrially mature MAM processes, describing their characteristics, benefits, and prospective developments applicable to SMEs.



MAM Criterias	PBF	DED	BJ	MEX	Weight
Costs efficiency	2	2	3	4	3
Ease of integration/use	1	1	3	5	3
Energy consumption	2	2	5	3	1
Production speed	1	2	5	1	1
Surface roughness	2	2	2	3	1
Dimensional accuracy	4	2	4	3	1
Mechanical quality	5	3	2	1	1
Market	5	2	1	1	1
Total Score	28	22	37	39	

MAM Criterias	PBF	DED	BJ	MEX	Weight
Costs efficiency	2	2	3	4	2
Ease of integration/use	1	1	3	5	1
Energy consumption	2	2	5	3	2
Production speed	1	2	5	1	1
Surface roughness	2	2	2	3	3
Dimensional accuracy	4	2	4	3	3
Mechanical quality	5	3	2	1	3
Market	5	2	1	1	2
Total Score	53	36	50	43	

MAM Criterias	PBF	DED	BJ	MEX	Weight
Costs efficiency	2	2	3	4	3
Ease of integration/use	1	1	3	5	2
Energy consumption	2	2	5	3	2
Production speed	1	2	5	1	3
Surface roughness	2	2	2	3	2
Dimensional accuracy	4	2	4	3	2
Mechanical quality	5	3	2	1	2
Market	5	2	1	1	2
Total Score	47	36	58	47	

🟥 Worst
🟧
🟨
🟩
🟩 Best

Fig. 4. Evaluation Matrix for MAM Processes: Examples for SMEs with different focuses.

5. Conclusion

This paper has provided an in-depth analysis of MAM processes in the context of SMEs. By examining various MAM processes, including PBF, DED, BJ, and MEX we have highlighted their unique attributes, advantages, and limitations, especially as they pertain to the operational and strategic frameworks of SMEs. The analysis underscores the diverse nature of MAM processes, each presenting distinct opportunities and challenges for SMEs. While PBF and DED offer high precision and suitability for complex part requirements, their high cost and technical complexity may pose significant barriers for SMEs with limited resources. On the other hand, BJ and MEX emerge as more accessible options, offering cost-effectiveness and operational simplicity, albeit with their own set of challenges related to technical maturity, part quality, and production speed. Crucially, the decision-making process for SMEs in adopting MAM is nuanced and context-dependent. It requires a careful balance between their specific needs, market demands, resource availability, and technological capabilities. The development of the evaluation matrix, presented as an illustrative example in this paper, serves as a guide to assist SMEs in assessing various MAM processes. It is important to note that this matrix is intended as a starting point for SMEs, encouraging a detailed and customized evaluation of each MAM process to determine the best fit for their individual requirements.

The study does have some limitations. First, the comparison diagram and evaluation matrix are based on currently available data, which may evolve as MAM technologies advance. The rapidly changing nature of these technologies means that the findings may need periodic updates to remain relevant. Second, the available data on MAM is fragmented and has considerable variation. Herein, the study relies on a generalized assessment of MAM processes, which may not capture all the specific nuances and contextual factors unique to individual SMEs. Third, the economic and operational conditions of SMEs vary widely, and while the study attempts to account for these variations, the recommendations may not be universally applicable. Lastly, the study does not include empirical validation through real-world case studies, which could provide deeper insights into the practical challenges and benefits of adopting MAM technologies in SMEs.

During the preparation of this work the author(s) used the AI language model ChatGPT by OpenAI in order to improve language and correct errors in writing. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

CRediT authorship contribution statement

Mathias Sæterbø: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Wei Deng Solvang:** Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

References

[1] Iso/astm:52900-2021(en), additive manufacturing – general principles – fundamentals and vocabulary. URL https://www.astm.org/f3177-21.html.

[2] Ngo TD, Kashani A, Imbalzano G, Nguyen KT, Hui D. Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. Composites B 2018;143:172–96. http://dx.doi.org/10.1016/j.compositesb.2018.02.012, URL https://www.sciencedirect.com/science/article/pii/S1359836817342944.

[3] Verboeket V, Krikke H. The disruptive impact of additive manufacturing on supply chains: A literature study, conceptual framework and research agenda. Comput Ind 2019;111:91–107. http://dx.doi.org/10.1016/j.compind.2019.07.003, URL https://www.sciencedirect.com/science/article/pii/S0166361519303446.

[4] Blakey-Milner B, Gradl P, Snedden G, Brooks M, Pitot J, Lopez E, et al. Metal additive manufacturing in aerospace: A review. Mater Des 2021;209:110008. http://dx.doi.org/10.1016/j.matdes.2021.110008, URL https://www.sciencedirect.com/science/article/pii/S0264127521005633.

[5] Salmi M. Additive manufacturing processes in medical applications. Materials 2021;14(1):191. http://dx.doi.org/10.3390/ma14010191, URL https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7796413/.

[6] Leal R, Barreiros FM, Alves L, Romeiro F, Vasco JC, Santos M, et al. Additive manufacturing tooling for the automotive industry. Int J Adv Manuf Technol 2017;92(5):1671–6. http://dx.doi.org/10.1007/s00170-017-0239-8.

[7] Bogers M, Hadar R, Bilberg A. Additive manufacturing for consumer-centric business models: Implications for supply chains in consumer goods manufacturing. Technol Forecast Soc Change 2016;102:225–39. http://dx.doi.org/10.1016/j.techfore.2015.07.024, URL https://www.sciencedirect.com/science/article/pii/S0040162515002437.

[8] Martinsuo M, Luomaranta T. Adopting additive manufacturing in SMEs: exploring the challenges and solutions. J Manuf Technol Manag 2018;29. http://dx.doi.org/10.1108/JMTM-02-2018-0030.

[9] Haug A, Wickstrøm KA, Stentoft J, Philipsen K. Adoption of additive manufacturing: A survey of the role of knowledge networks and maturity in small and medium-sized danish production firms. Int J Prod Econ 2023;255:108714. http://dx.doi.org/10.1016/j.ijpe.2022.108714, URL https://www.sciencedirect.com/science/article/pii/S0925527322002961.

[10] Mellor S, Hao L, Zhang D. Additive manufacturing: A framework for implementation. Int J Prod Econ 2014;149:194–201. http://dx.doi.org/10.1016/j.ijpe.2013.07.008, URL https://www.sciencedirect.com/science/article/pii/S0925527313003204, The Economics of Industrial Production.

[11] Deradjat D, Minshall T. Implementation of rapid manufacturing for mass customisation. 2016, http://dx.doi.org/10.17863/CAM.4528.

[12] Niaki MK, Torabi SA, Nonino F. Why manufacturers adopt additive manufacturing technologies: The role of sustainability. J Clean Prod 2019;222:381–92. http://dx.doi.org/10.1016/j.jclepro.2019.03.019, URL https://www.sciencedirect.com/science/article/pii/S0959652619307024.

[13] González-Varona JM, Poza D, Acebes F, Villafáñez F, Pajares J, López-Paredes A. New business models for sustainable spare parts logistics: A case study. Sustainability 2020;12(8). URL https://www.mdpi.com/2071-1050/12/8/3071.

[14] Vafadar A, Guzzomi F, Rassau A, Hayward K. Advances in metal additive manufacturing: A review of common processes, industrial applications, and current challenges. Appl Sci 2021;11(3). URL https://www.mdpi.com/2076-3417/11/3/1213.

[15] SME definition, URL https://single-market-economy.ec.europa.eu/smes/sme-definition_en.

[16] Moeuf A, Pellerin R, Lamouri S, Tamayo-Giraldo S, Barbaray R. The industrial management of SMEs in the era of industry 4.0. Int J Prod Res 2018;56(3):1118–36. http://dx.doi.org/10.1080/00207543.2017.1372647.

[17] Oum S, Narjoko D, Harvie C. Constraints, Determinants of SME Innovation, and the Role of Government Support.

[18] Pereira R, Franco M. Cooperation between universities and SMEs: A systematic literature review. Ind Higher Educ 2022;36(1):37–50. http://dx.doi.org/10.1177/0950422221995114.

[19] Falkner E, Hiebl M. Risk management in SMEs: a systematic review of available evidence. J Risk Financ 2015;16:122–44. http://dx.doi.org/10.1108/JRF-06-2014-0079.

[20] Lasagni A. How can external relationships enhance innovation in SMEs? New evidence for europe*. J Small Bus Manag 2012;50(2):310–39. http://dx.doi.org/10.1111/j.1540-627X.2012.00355.x, arXiv:https://www.tandfonline.com/doi/pdf/10.1111/j.1540-627X.2012.00355.x, URL https://www.tandfonline.com/doi/abs/10.1111/j.1540-627X.2012.00355.x.

[21] Gherghina C, Botezatu MA, Hosszu A, Simionescu LN. Small and medium-sized enterprises (SMEs): The engine of economic growth through investments and innovation. Sustainability 2020;12(1). http://dx.doi.org/10.3390/su12010347, URL https://www.mdpi.com/2071-1050/12/1/347.

[22] Ali FH, Ali M, Malik SZ, Hamza MA, Ali HF. Managers' open innovation and business performance in SMEs: A moderated mediation model of job crafting and gender. J Open Innov: Technol Mark Complex 2020;6(3):89. http://dx.doi.org/10.3390/joitmc6030089, URL https://www.sciencedirect.com/science/article/pii/S2199853122005820.

[23] Galli-Debicella A. How SMEs compete against global giants through sustainable competitive advantages. J Small Bus Strategy 2021;31. http://dx.doi.org/10.53703/001c.29812.

[24] Kulkarni P, Kumar A, Chate G, Dandannavar P. Elements of additive manufacturing technology adoption in small- and medium-sized sized companies. Innov Manag Rev 2021;ahead-of-print. http://dx.doi.org/10.1108/INMR-02-2020-0015.

[25] Shah S, Mattiuzza S. Adoption of additive manufacturing approaches: The case of manufacturing SMEs. In: 2018 IEEE international conference on engineering, technology and innovation (ICE/ITMC). 2018, p. 1–8. http://dx.doi.org/10.1109/ICE.2018.8436257.

[26] Produção G, Calderaro D, Lacerda D, Veit D. Selection of additive manufacturing technologies in productive systems: a decision support model. Gestão & Produção 2020;27. http://dx.doi.org/10.1590/0104-530x5363-20.

[27] Niaki MK, Nonino F. Additive manufacturing management: a review and future research agenda. Int J Prod Res 2017;55(5):1419–39. http://dx.doi.org/10.1080/00207543.2016.1229064.

[28] Mahapatra S, Panda B. Benchmarking of rapid prototyping systems using grey relational analysis. Int J Serv Oper Manag 2013;16:460–77. http://dx.doi.org/10.1504/IJSOM.2013.057509.

[29] Maranha J, Nascimento PJ, Calcerano T, Silva C, Mueller S, Moniz S. A decision-support framework for selecting additive manufacturing technologies. J Manuf Technol Manag 2023;34:1279–311. http://dx.doi.org/10.1108/JMTM-02-2023-0047.

[30] Ahmed M, Chan KJD, McFarlane D. A game theoretic approach to assessing additive manufacturing as a strategic choice. In: 2018 iNTERNATIONAL cONFERENCE on pRODUCTION and oPERATIONS mANAGEMENT SOCIETY. POMS, IEEE Sri Lanka Sect; Prod & Operat Management Soc; Mfg Engn Assoc; Univ Peradeniya; IEEE Sri Lanka Chapter; Inst Engineers Sri Lanka; Chartered Inst Logist & Transport; CEYLEX Engn Pvt Ltd; MAS; Dassault Systemes; Noritake; Selma Technologies Pvt Ltd; John Keells Logist; 2018, International Conference on Production and Operations Management Society (POMS), Kandy, SRI LANKA, DEC 14-16, 2018.

[31] Bikas H, Koutsoukos S, Stavropoulos P. A decision support method for evaluation and process selection of additive manufacturing. Proc CIRP 2019;81:1107–12. http://dx.doi.org/10.1016/j.procir.2019.03.261, URL https://www.sciencedirect.com/science/article/pii/S2212827119305669, 52nd CIRP Conference on Manufacturing Systems (CMS), Ljubljana, Slovenia, June 12-14, 2019.

[32] Bertolini M, Esposito G, Romagnoli G. A TOPSIS-based approach for the best match between manufacturing technologies and product specifications. Expert Syst Appl 2020;159:113610. http://dx.doi.org/10.1016/j.eswa.2020.113610, URL https://www.sciencedirect.com/science/article/pii/S0957417420304346.

[33] Park H-S, Tran N-H. A decision support system for selecting additive manufacturing technologies. In: Proceedings of the 2017 international conference on information system and data mining. ICISDM '17, New York, NY, USA: Association for Computing Machinery; 2017, p. 151–5. http://dx.doi.org/10.1145/3077584.3077606.

[34] Rinaldi M, Caterino M, Fera M, Manco P, Macchiaroli R. Technology selection in green supply chains - the effects of additive and traditional manufacturing. J Clean Prod 2021;282:124554. http://dx.doi.org/10.1016/j.jclepro.2020.124554, URL https://www.sciencedirect.com/science/article/pii/S0959652620345984.

[35] Raigar J, Sharma V, Srivastava S, Chand R, Singh J. A decision support system for the selection of an additive manufacturing process using a new hybrid MCDM technique. Sadhana 2020;45:1–14. http://dx.doi.org/10.1007/s12046-020-01338-w.

[36] Wang Y, Zhong R, Xu X. A decision support system for additive manufacturing process selection using a hybrid multiple criteria decision-making method. Rapid Prototyp J 2018;24. http://dx.doi.org/10.1108/RPJ-01-2018-0002.

[37] Algunaid K, Liu J. Decision support system to select a 3D printing process/machine and material from a large-scale options pool. Int J Adv Manuf Technol 2022;121:1–17. http://dx.doi.org/10.1007/s00170-022-09362-2.

[38] Pratheesh Kumar S, Elangovan S, Mohanraj R, Ramakrishna J. Review on the evolution and technology of state-of-the-art metal additive manufacturing processes. Mater Today: Proc 2021;46:7907–20. http://dx.doi.org/10.1016/j.matpr.2021.02.567, URL https://www.sciencedirect.com/science/article/pii/S2214785321017120, 3rd International Conference on Materials, Manufacturing and Modelling.

[39] Mahmood A, Akram T, Chen H, Chen S. On the evolution of additive manufacturing (3D/4D printing) technologies: Materials, applications, and challenges. Polymers 2022;14(21). http://dx.doi.org/10.3390/polym14214698, URL https://www.mdpi.com/2073-4360/14/21/4698.

[40] Gibson I, Rosen D, Stucker B. Powder bed fusion processes. In: Gibson I, Rosen D, Stucker B, editors. Additive manufacturing technologies: 3D printing, rapid prototyping, and direct digital manufacturing. New York, NY: Springer; 2015, p. 107–45. http://dx.doi.org/10.1007/978-1-4939-2113-3_5.

[41] Armstrong M, Mehrabi H, Naveed N. An overview of modern metal additive manufacturing technology. J Manuf Process 2022;84:1001–29. http://dx.doi.org/10.1016/j.jmapro.2022.10.060, URL https://www.sciencedirect.com/science/article/pii/S1526612522007459.

[42] Khorasani A, Gibson I, Veetil JK, Ghasemi AH. A review of technological improvements in laser-based powder bed fusion of metal printers. Int J Adv Manuf Technol 2020;108(1):191–209. http://dx.doi.org/10.1007/s00170-020-05361-3.

[43] Haines MP, Peter NJ, Babu SS, Jägle EA. In-situ synthesis of oxides by reactive process atmospheres during L-PBF of stainless steel. Addit Manuf 2020;33:101178. http://dx.doi.org/10.1016/j.addma.2020.101178, URL https://www.sciencedirect.com/science/article/pii/S2214860420305509.

[44] Ahn D-G. Direct metal additive manufacturing processes and their sustainable applications for green technology: A review. Int J Precis Eng Manuf-Green Technol 2016;3:381–95. http://dx.doi.org/10.1007/s40684-016-0048-9.

[45] Ahn D-G. Directed energy deposition (DED) Process: State of the art. Int J Precis Eng Manuf-Green Technol 2021;8(2):703–42. http://dx.doi.org/10.1007/s40684-020-00302-7.

[46] Garcia-Colomo A, Wood D, Martina F, Williams S. A comparison framework to support the selection of the best additive manufacturing process for specific aerospace applications. Int J Rap Manuf 2019;9. http://dx.doi.org/10.1504/IJRAPIDM.2020.10019230.

[47] Svetlizky D, Das M, Zheng B, Vyatskikh AL, Bose S, Bandyopadhyay A, et al. Directed energy deposition (DED) additive manufacturing: Physical characteristics, defects, challenges and applications. Mater Today 2021;49:271–95. http://dx.doi.org/10.1016/j.mattod.2021.03.020, URL https://www.sciencedirect.com/science/article/pii/S1369702121001139.

[48] Suwanpreecha C, Manonukul A. A review on material extrusion additive manufacturing of metal and how it compares with metal injection moulding. Metals 2022;12(3). URL https://www.mdpi.com/2075-4701/12/3/429.

[49] Sachs E, Cima M, Williams P, Brancazio D, Cornie J. Three dimensional printing: Rapid tooling and prototypes directly from a CAD model. J Eng Ind 1992;114(4):481–8. http://dx.doi.org/10.1115/1.2900701, arXiv:https://asmedigitalcollection.asme.org/manufacturingscience/article-pdf/114/4/481/6507111/481_1.pdf.

[50] Ziaee M, Crane NB. Binder jetting: A review of process, materials, and methods. Addit Manuf 2019;28:781–801. http://dx.doi.org/10.1016/j.addma.2019.05.031, URL https://www.sciencedirect.com/science/article/pii/S2214860418310078.

[51] AMPOWER report 2020 metal additive manufacturing management summarys. 2020.

[52] Additive Manufacturing Technology explained in 18 processes. 2021, URL https://additive-manufacturing-report.com/additive-manufacturing-metal-technology/.

[53] Piscopo G, Salmi A, Atzeni E. Investigation of dimensional and geometrical tolerances of laser powder directed energy deposition process. Precis Eng 2024;85:217–25. http://dx.doi.org/10.1016/j.precisioneng.2023.10.006, URL https://www.sciencedirect.com/science/article/pii/S0141635923001897.

[54] Galati M, Minetola P. Analysis of density, roughness, and accuracy of the atomic diffusion additive manufacturing (ADAM) process for metal parts. Materials 2019;12(24). http://dx.doi.org/10.3390/ma12244122, URL https://www.mdpi.com/1996-1944/12/24/4122.

[55] Mostafaei A, Elliott AM, Barnes JE, Li F, Tan W, Cramer CL, et al. Binder jet 3D printing—Process parameters, materials, properties, modeling, and challenges. Prog Mater Sci 2021;119:100707. http://dx.doi.org/10.1016/j.pmatsci.2020.100707, URL https://www.sciencedirect.com/science/article/pii/S0079642520300712.

[56] The Best Metal 3D Printers in 2024 | All3DP Pro, https://all3dp.com/1/3d-metal-3d-printer-metal-3d-printing/#markforged-metal-x, (Accessed on 05/10/2024).

[57] 3D printer catalog: Over 2, 300 3D printers to choose from, https://www.aniwaa.com/catalog/3d-printers/, (Accessed on 05/11/2024).

[58] Singh P, Balla VK, Atre SV, German RM, Kate KH. Factors affecting properties of Ti-6Al-4V alloy additive manufactured by metal fused filament fabrication. Powder Technol 2021;386:9–19. http://dx.doi.org/10.1016/j.powtec.2021.03.026, URL https://www.sciencedirect.com/science/article/pii/S0032591021002175.

[59] Bai Y, Williams C. An exploration of binder jetting of copper. Rapid Prototyp J 2015;21:177–85. http://dx.doi.org/10.1108/RPJ-12-2014-0180.

[60] Rott S, Ladewig A, Friedberger K, Casper J, Full M, Schleifenbaum JH. Surface roughness in laser powder bed fusion – Interdependency of surface orientation and laser incidence. Addit Manuf 2020;36:101437. http://dx.doi.org/10.1016/j.addma.2020.101437, URL https://www.sciencedirect.com/science/article/pii/S2214860420308095.

[61] Piscopo G, Salmi A, Atzeni E. Influence of high-productivity process parameters on the surface quality and residual stress state of AISI 316L components produced by directed energy deposition. J Mater Eng Perform 2021;30(9):6691–702. http://dx.doi.org/10.1007/s11665-021-05954-3.

[62] Opoz TT, Burgess A, Ahuir-Torres JI, Kotadia HR, Tammas-Williams S. The effect of surface finish and post-processing on mechanical properties of 17-4 PH stainless steel produced by the atomic diffusion additive manufacturing process (ADAM). Int J Adv Manuf Technol 2024;130(7):4053–66. http://dx.doi.org/10.1007/s00170-024-12949-6.

[63] Zhang B, Zhan Z, Cao Y, Gulan H, Linnér P, Sun J, et al. Metallic 3-D printed antennas for millimeter- and submillimeter wave applications. IEEE Trans Terahertz Sci Technol 2016;6(4):592–600. http://dx.doi.org/10.1109/TTHZ.2016.2562508.

[64] Gruber S, Grunert C, Riede M, López E, Marquardt A, Brueckner F, et al. Comparison of dimensional accuracy and tolerances of powder bed based and nozzle based additive manufacturing processes. J Laser Appl 2020;32(3):032016. http://dx.doi.org/10.2351/7.0000115.

[65] Rupal BS, Singh T, Wolfe T, Secanell M, Qureshi AJ. Tri-planar geometric dimensioning and tolerancing characteristics of SS 316L laser powder bed fusion process test artifacts and effect of base plate removal. Materials 2021;14(13). http://dx.doi.org/10.3390/ma14133575, URL https://www.mdpi.com/1996-1944/14/13/3575.

[66] Williams SW, Martina F, Addison AC, Ding J, Pardal G, Colegrove P. Wire + arc additive manufacturing. Mater Sci Technol 2016;32(7):641–7. http://dx.doi.org/10.1179/1743284715Y.0000000073.

[67] Jiménez A, Bidare P, Hassanin H, Tarlochan F, Dimov S, Essa K. Powder-based laser hybrid additive manufacturing of metals: a review. Int J Adv Manuf Technol 2021;114(1):63–96. http://dx.doi.org/10.1007/s00170-021-06855-4.

[68] Sercombe TB, Xu X, Challis V, Green R, Yue S, Zhang Z, et al. Failure modes in high strength and stiffness to weight scaffolds produced by selective laser melting. Mater Des 2015;67:501–8. http://dx.doi.org/10.1016/j.matdes.2014.10.063, URL https://www.sciencedirect.com/science/article/pii/S0261306914008516.

[69] Ye C, Zhang C, Zhao J, Dong Y. Effects of post-processing on the surface finish, porosity, residual stresses, and fatigue performance of additive manufactured metals: A review. J Mater Eng Perform 2021;30:6407–25. http://dx.doi.org/10.1007/s11665-021-06021-7.

[70] Narasimharaju SR, Zeng W, See TL, Zhu Z, Scott P, Jiang X, et al. A comprehensive review on laser powder bed fusion of steels: Processing, microstructure, defects and control methods, mechanical properties, current challenges and future trends. J Manuf Process 2022;75:375–414. http://dx.doi.org/10.1016/j.jmapro.2021.12.033, URL https://www.sciencedirect.com/science/article/pii/S1526612521009178.

[71] Hitzler L, Hirsch J, Heine B, Merkel M, Hall W, Öchsner A. On the anisotropic mechanical properties of selective laser-melted stainless steel. Materials 2017;10(10). http://dx.doi.org/10.3390/ma10101136, URL https://www.mdpi.com/1996-1944/10/10/1136.

[72] Oliveira J, LaLonde A, Ma J. Processing parameters in laser powder bed fusion metal additive manufacturing. Mater Des 2020;193:108762. http://dx.doi.org/10.1016/j.matdes.2020.108762, URL https://www.sciencedirect.com/science/article/pii/S0264127520302963.

[73] Schwerz C, Schulz F, Natesan E, Nyborg L. Increasing productivity of laser powder bed fusion manufactured Hastelloy X through modification of process parameters. J Manuf Process 2022;78:231–41. http://dx.doi.org/10.1016/j.jmapro.2022.04.013, URL https://www.sciencedirect.com/science/article/pii/S1526612522002419.

[74] ASTM F3413-2019: Guide for additive manufacturing – design – directed energy deposition, URL https://www.astm.org/f3187-16.html.

[75] Dass A, Moridi A. State of the art in directed energy deposition: From additive manufacturing to materials design. Coatings 2019;9(7). http://dx.doi.org/10.3390/coatings9070418, URL https://www.mdpi.com/2079-6412/9/7/418.

[76] Piscopo G, Iuliano L. Current research and industrial application of laser powder directed energy deposition. Int J Adv Manuf Technol 2022;119(11):6893–917. http://dx.doi.org/10.1007/s00170-021-08596-w.

[77] Rane K, Strano M. A comprehensive review of extrusion-based additive manufacturing processes for rapid production of metallic and ceramic parts. Adv Manuf 2019;7(2):155–73. http://dx.doi.org/10.1007/s40436-019-00253-6.

[78] Acevedo R, Sedlak P, Kolman R, Fredel M. Residual stress analysis of additive manufacturing of metallic parts using ultrasonic waves: State of the art review. J Mater Res Technol 2020;9(4):9457–77. http://dx.doi.org/10.1016/j.jmrt.2020.05.092, URL https://www.sciencedirect.com/science/article/pii/S2238785420313600.

[79] Roth GA, Geraci CL, Stefaniak A, Murashov V, Howard J. Potential occupational hazards of additive manufacturing. J Occup Environ Hyg 2019;16(5):321–8. http://dx.doi.org/10.1080/15459624.2019.1591627, URL https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6555134/.

[80] Watson A, Belding J, Ellis BD. Characterization of 17-4 PH processed via bound metal deposition (BMD). In: TMS 2020 149th annual meeting & exhibition supplemental proceedings. The minerals, metals & materials series, Cham: Springer International Publishing; 2020, p. 205–16. http://dx.doi.org/10.1007/978-3-030-36296-6_19.

[81] Gonzalez-Gutierrez J, Cano S, Schuschnigg S, Kukla C, Sapkota J, Holzer C. Additive manufacturing of metallic and ceramic components by the material extrusion of highly-filled polymers: A review and future perspectives. Materials 2018;11(5). http://dx.doi.org/10.3390/ma11050840, URL https://www.mdpi.com/1996-1944/11/5/840.

[82] Li M, Du W, Elwany A, Pei Z, Ma C. Metal binder jetting additive manufacturing: A literature review. J Manuf Sci Eng 2020;142(9):090801. http://dx.doi.org/10.1115/1.4047430, _eprint: https://asmedigitalcollection.asme.org/manufacturingscience/article-pdf/142/9/090801/6545406/manu_142_9_090801.pdf.

[83] Asier Lores IA, Zuza E. A review on recent developments in binder jetting metal additive manufacturing: materials and process characteristics. Powder Metall 2019;62(5):267–96. http://dx.doi.org/10.1080/00325899.2019.1669299.

[84] Chan FTS, Chan MH, Tang NKH. Evaluation methodologies for technology selection. J Mater Process Technol 2000;107(1):330–7. http://dx.doi.org/10.1016/S0924-0136(00)00679-8, URL https://www.sciencedirect.com/science/article/pii/S0924013600006798.

[85] Lindemann C, Jahnke UD, Moi M, Koch R. Analyzing product lifecycle costs for a better understanding of cost drivers in additive manufacturing. 2012, URL https://api.semanticscholar.org/CorpusID:21183001.

[86] Flores I, Kretzschmar N, Azman AH, Chekurov S, Pedersen DB, Chaudhuri A. Implications of lattice structures on economics and productivity of metal powder bed fusion. Addit Manuf 2020;31:100947. http://dx.doi.org/10.1016/j.addma.2019.100947, URL https://www.sciencedirect.com/science/article/pii/S2214860419308292.

[87] Malekipour E, El-Mounayri H. Common defects and contributing parameters in powder bed fusion AM process and their classification for online monitoring and control: a review. Int J Adv Manuf Technol 2018;95(1):527–50. http://dx.doi.org/10.1007/s00170-017-1172-6.

[88] Gisario A, Kazarian M, Martina F, Mehrpouya M. Metal additive manufacturing in the commercial aviation industry: A review. J Manuf Syst 2019;53:124–49. http://dx.doi.org/10.1016/j.jmsy.2019.08.005, URL https://www.sciencedirect.com/science/article/pii/S0278612519300731.

[89] Zhang Y, Wu L, Guo X, Kane S, Deng Y, Jung Y-G, et al. Additive manufacturing of metallic materials: A review. J Mater Eng Perform 2018;27(1):1–13. http://dx.doi.org/10.1007/s11665-017-2747-y.

[90] Godec D, Cano S, Holzer C, Gonzalez-Gutierrez J. Optimization of the 3D printing parameters for tensile properties of specimens produced by fused filament fabrication of 17-4PH stainless steel. Materials 2020;13(3). http://dx.doi.org/10.3390/ma13030774, URL https://www.mdpi.com/1996-1944/13/3/774.

[91] Gonzalez-Gutierrez J, Godec D, Guráň R, Spoerk M, Kukla C, Holzer C. 3D printing conditions determination for feedstock used in fused filament fabrication (FFF) of 17-4PH stainless steel parts. Metalurgija -Sisak then Zagreb-2017;57:117–20.

[92] Metal D. Studio System™, URL https://www.desktopmetal.com/products/studio.