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Sustainability in Additive Manufacturing

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Abstract

Additive manufacturing is positioned as a key enabler for sustainable production due to its inherent characteristics connected to near-net shape manufacturing, resulting in high material efficiency, as well as individualized and flexible manufacturing of complex 3D shaped objects on-demand. In addition, feedstock materials can be either reused in case of metal or sourced sustainably in case of renewable bio-based polymers. Further economic and social benefits can be realized along the supply chain and life cycle of the materials and products, depending on the selected technology, material, and application. This article provides an overview of additive manufacturing developments, their potential sustainability benefits and challenges along with concrete examples of different technologies and applications, and barriers to adoption.

Keywords

Additive Manufacturing, 3D Printing, Sustainable Development, Review, Environmental Technology, Eco-Innovation

List of acronyms/nomenclature

3D: Three-dimensional
3MF: 3D Manufacturing Format (file format)
4D: Four-dimensional
ABS: Acrylonitrile Butadiene Styrene
AI: Artificial Intelligence
AM: Additive Manufacturing
ASTM: American Society for Testing and Materials
BJT: Binder Jetting
CAD: Computer-Aided Design
CAM: Computer-Aided Manufacturing
CLIP: Continuous Liquid Interface Production
DED: Directed Energy Deposition
DLS: Digital Light Synthesis
DIY: Do It Yourself
DOD: Drop-On-Demand
EBM: Electron Beam Melting
EBAM: Electron Beam Additive Manufacturing
FDM: Fused Deposition Modelling
FFF: Fused Filament Fabrication/Filament Freeform Fabrication
HSS: High-Speed Sintering
ICT: Information and Communication Technology
IoT: Internet of Things
ISO: International Organization for Standardization
LCA: Life Cycle Analysis
LCM: Lithography-based Ceramic Manufacturing
LEM: Laminated Engineering Materials
LENS: Laser-Engineered Net Shaping
LMD(-w): Laser Metal Deposition (- Wire)
LOM: Laminated Object Manufacturing
MEX: Material Extrusion
MJM: Multijet Modeling
ML: Machine Learning
PA: Polyamide
PBF-EB/LB: Powder Bed Fusion - Electron Beam/Laser Beam
PEEK: Polyether ether ketone
PEI: Polyetherimide
PLA: Polylactic Acid
PLM: Product Lifecycle Management
SLA: Stereolithography
SLS: Selective Laser Sintering
SLM: Selective Laser Melting
STL: Stereolithography (file format)
UV: Ultraviolet
UAM: Ultrasonic Additive Manufacturing
VAT: Vat Photopolymerization
WAAM: Wire Arc Additive Manufacturing

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Chapter objectives

- Introduce AM with its definition and a brief history of key technological developments
- Provide an overview of the state of the art in AM processes and applications
- Compare AM with other conventional manufacturing techniques
- Present the sustainability advantages and challenges of AM
- Discuss the barriers to AM adoption, focusing on industrial challenges
- Provides some illustrative examples of AM applications with their sustainability implications

Introduction and definition

Additive manufacturing (AM), often referred to as "3D printing", is the process of producing a physical object based on a digital model by adding material layer by layer. This broad family of manufacturing technologies has been applied to various materials, including polymers, metals, ceramics, and composites. AM encompasses the entire process of designing, optimizing, and manufacturing final components and products, but also includes rapid prototyping, tooling, repair, remanufacturing, and other circular processes, in addition to direct functional part production. The main fields of application and industries using AM are aerospace, automotive, medical and consumer products.

The international standard ISO/ASTM52900-15 defines seven categories of AM processes: (1) vat photopolymerization, (2) material jetting, (3) binder jetting, (4) powder bed fusion, (5) material extrusion, (6) directed energy deposition, and (7) sheet lamination. See recommended reading in **side box A** for more information with AM standard terminology and development trends.

Recommended reading about terminology and trends (side box A)

• ISO/ASTM 52900:2021 (Additive manufacturing — General principles — Fundamentals and vocabulary) are international standards establishing the terminology for additive manufacturing technologies, categories of processes, and array of materials.

• To keep up to date with AM technologies, a number of yearly reports provide insights into the latest developments and trends in additive manufacturing (e.g., Wohlers Report published annually by Wohlers Associates, AMPOWER report, etc.).

Besides this process-based categorization, AM can also be categorized based on the feedstock material used (polymer, metal or ceramic) and physical state (powder, solid or liquid), as presented in Table 1. Metal AM technologies can be broadly categorized as powder bed, powder fed, and wire fed systems. Metal-based AM processes include powder bed fusion - electron beam (PBF-EB) (often referred to as electron beam melting (EBM)), powder bed fusion - laser beam of metals (PBF-LB/M), powder-fed directed energy deposition (DED), and wire-fed directed energy deposition, which depending on the

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energy source used is divided into arc-DED (also known as wire arc additive manufacturing (WAAM)), laser-DED (often referred to as laser metal deposition - wire (LMD-w)) and electron beam DED (also known as Electron Beam Additive Manufacturing (EBAM), and metal binder jetting (BJT). Polymer-based AM processes typically include vat photopolymerization (VAT), often referred to as stereolithography (SLA), material extrusion (MEX) (often referred to as fused deposition modelling (FDM) or fused filament fabrication/filament freeform fabrication (FFF)) and laser-based powder bed fusion of polymers (PBF-LB/P) (often referred to as selective laser sintering (SLS)). Ceramic-based AM processes include vat photopolymerization, often referred to as lithography-based ceramic manufacturing (LCM), binder jetting (BJT/C), or sheet lamination, also known as computer-aided manufacturing of laminated engineering materials (CAM-LEM).

Table 1. AM process categories, feedstock materials and formats, and examples.

Process category	***Feedstock material***	***Material state***	***Examples of technologies and proprietary solutions***
Vat photopolymerization (VAT)	Polymer	Liquid/suspension	Digital light synthesis (DLS)*, Stereolithography (SLA), Continuous liquid interface production (CLIP)*
Material jetting	Polymer	Liquid/suspension	Inkjet 3D printing, Multijet modeling (MJM), Nano particle jetting
Binder jetting (BJT)	Polymer/Metal/Ceramic	Liquid + powder	Metal binder jetting (BJT/M), Ceramic binder jetting (BJT/C), Powder bed and inkjet head
Powder bed fusion (PBF)	Polymer/Metal/Ceramic	Powder	Electron beam melting (EBM)*, Selective laser melting (SLM)*, Direct metal laser sintering*, High-speed sintering (HSS)*, Selective electron beam melting, Selective laser sintering (SLS)
Material extrusion (MEX)	Polymer	Filament	Fused deposition modeling (FDM), Fused filament fabrication (FFF)
Directed energy deposition (DED)	Metal	Filament/Powder	Wire arc additive manufacturing (WAAM), Laser-engineered net shaping (LENS)*, Laser metal deposition (LMD)
Sheet lamination	Polymer/Metal	Sheet	Ultrasonic additive manufacturing (UAM), Laminated object manufacturing (LOM)*

* Non-standard, proprietary names

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A brief historical review

This section presents the technology timeline, with Figure 1 illustrating important development milestones, including elements presented in the next section on the technology state of the art.

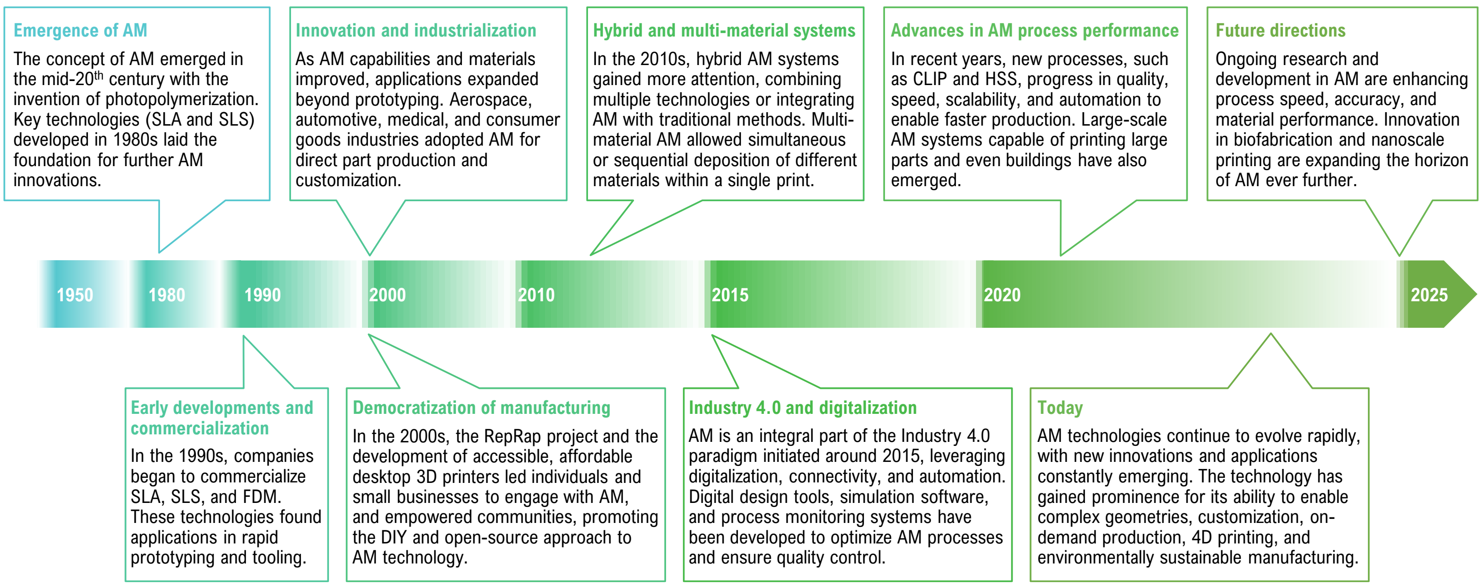

Figure 1. A brief historical review of milestones in AM technological development.

The origin of AM dates back to the mid-20th century with the patent registered by Otto John Munz in 1951, including the key elements of the modern photopolymerization technologies (Diegel, Nordin and Motte, 2019). Later, in 1980s, the modern AM technologies emerged with SLA, SLS and FDM, focused on polymers. SLA was concurrently developed in Japan, France and the US. While Hideo Kodama of Nagoya Municipal Industrial Research Institute invented the layering methods to fabricate 3D objects using a UV laser to selectively solidify a liquid photo-polymerizing resin through a photochemical process, the invention is often accredited to Charles Hull, an engineer at 3D Systems, who coined the term stereolithography. The French inventors Alain Le Méhauté, Olivier de Witte and Jean Claude André managed to file their patent for the SLA process just before Charles Hull filed his own patent. This technique is widely used today for rapid prototyping as part of product development as well as to industrial manufacturing of variety of components such as hearing aid shells, shoe soles, etc. SLS was later developed by Dr. Carl Deckard and Dr. Joseph Beaman at the University of Texas at Austin to selectively fuse powdered material using a laser. FDM was invented by Scott Crump, co-founder of Stratasys, to extrude a thermoplastic filament through a heated print head depositing material to create the desired shape.

Later in the 1990s, several variations of PBF technologies emerged which use a high-energy source to selectively melt or sinter powdered material to build the objects layer by layer. As AM technologies expanded and improved, various industries adopted them, further advancing the technologies'

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capabilities, most notably in the aerospace, automotive and healthcare sectors. With rapid developments in processes (both software and hardware) and materials, novel complex and functional components could be produced with increased precision, speed, efficiency and quality.

As industrial AM technologies and applications continued to progress, the mid-2000s saw the rise of a popular manufacturing paradigm with RepRap, an open-source project initiated by Dr. Adrian Bowyer (Jones *et al.*, 2011). This project brought about a new wave in the DIY movement with an affordable desktop manufacturing system, leading to the democratization of 3D printing technology. As predicted by the Gartner Hype Cycle shown in Figure 2, emerging technologies typically follow the phases of rapidly growing enthusiasm to reach the "peak of inflated expectations" before the "through of disillusionment" where users and consumers realize the limitations of the technology, and finally moving to a second wave of growth as expectations rise once again more gradually to reach the "plateau of productivity" (Fenn and Raskino, 2008). Different AM technologies and applications have moved through these maturity stages at different paces with the help of combined efforts from research, industry developments, and community support to propel the technology to its place in society today.

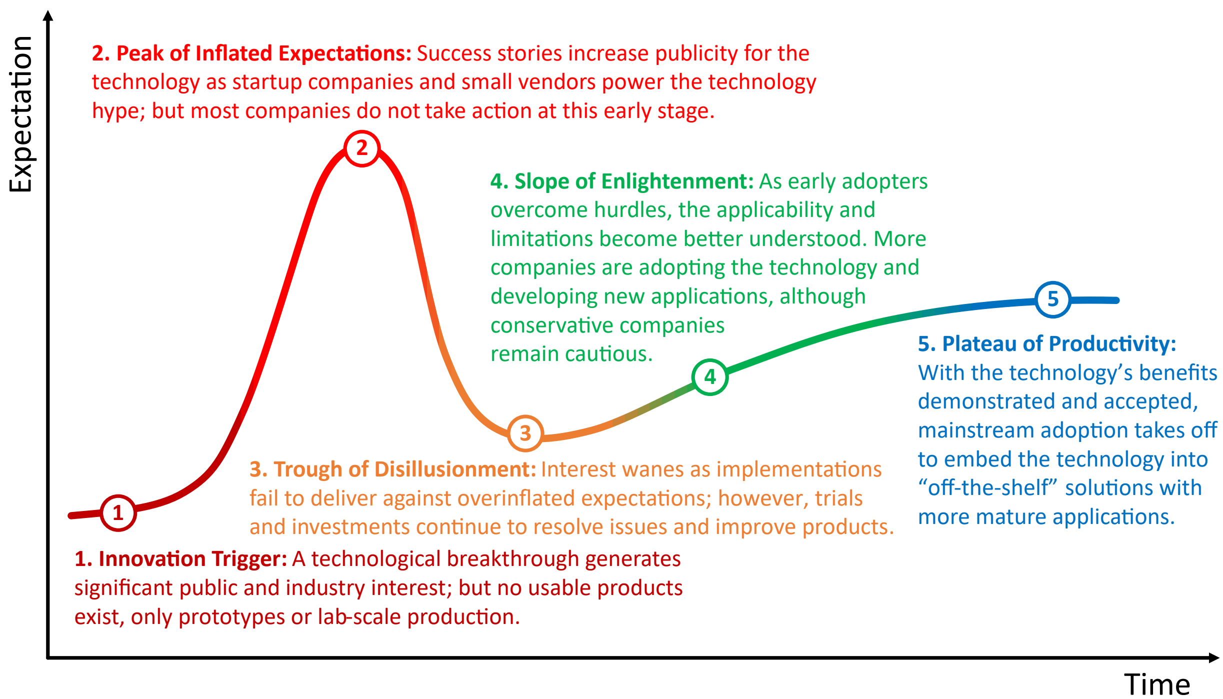

Figure 2. The Gartner "Hype Cycle" as part of the technology maturity model; adapted from (Fenn and Raskino, 2008).

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State of the art

While AM is still evolving, some recent advancements are especially noteworthy.

In metal AM, numerous processing conditions are synchronized to assure stable AM process and manufacturing of defect-free AM components. Process parameters related to the energy source include power, focus, scan speed, scanning pattern, etc. (Leicht *et al.*, 2020). Powder bed properties include powder physical and chemical properties, powder layer thickness, etc. Processing gas parameters include flow and its profile, type and quality of the gas, vacuum as processing environment, etc. (Pauzon *et al.*, 2020). These various parameters result in complex thermal history at each of the sites and hence formation of specific microstructure and residual stresses due to repeated melting and solidification (Pauzon *et al.*, 2021). However, this condition will also strongly depend on component size, shape and geometrical complexity, support structures (type, density, etc.) and orientation in the build volume in relation to the powder spreading, gas flow and scanning by energy source, etc. Hence, these attributes must be considered during component and process design to assure robust manufacturing of defect-free components. As metal components in as-printed state possess rapidly solidified microstructure with often high residual stresses and rather poor surface finish, recently more and more focus is placed on post-AM treatment of as-printed components to reach optimal microstructure and material properties with no or minimal residual stresses and defects (e.g. porosity or cracking) as well as improved surface finish.

Layer-by-layer manufacturing provides unlimited possibility for customized manufacturing with almost no additional cost involved that, however, requires robust processes to assure part-to-part consistency. Therefore, technology providers are focusing on the development and integration of in-situ process monitoring systems, such as optical tomography, melt pool monitoring, powder-bed monitoring, process gas/vacuum monitoring, etc., allowing to increase process robustness and assist with component qualification (Pauzon *et al.*, 2021).

One of the main challenges with metal AM is rather low manufacturing rate due to layer-by-layer manufacturing, requiring up to 50 layers to build 1 mm of the component height. Hence, much efforts and development are focused on increasing productivity of the metal AM processes by increasing layer thickness (Leicht *et al.*, 2020), increasing the number of laser sources in case of laser-based systems (Khorasani *et al.*, 2020) or increasing energy in case of electron-beam systems (Fu and Körner, 2022). Significant progress was made in the case of PBF to decrease and even fully eliminate support structures. Significant improvements were made to the scanning and control of the energy source allowed PBF-LB and PBF-EB to increase precision and accuracy levels, enabling the production of complex metal parts with intricate geometries. Furthermore, novel metal alloys and composites, multi-material processes and multi-functional materials, as well as the ability to embed objects within the AM-produced components, have unlocked new levels of product performance.

Regarding polymer technologies, great advancements were made in materials to increase their sustainability and performance; for example, polylactic acid (PLA) can be produced from renewable sources and recycled without loss of its original properties. Other commonly used polymers include acrylonitrile butadiene styrene (ABS), polyamide/nylon (P6 for filament, PA11 and PA12 for powders), etc. and variety of liquid polymers for material jetting and vat photopolymerization technologies,

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including acrylic and epoxy photopolymers and their mixtures, that can be also used with meta or ceramic nano-particle filler, waxy polymers, etc. to enhance material performance. New high-performance polymers—such as polyether ether ketone (PEEK), polyetherimide (PEI) as well as composite fillers with e.g. carbon or glass fibers, used in MEX—have also been developed to produce stronger, more durable, heat-resistant and chemically stable parts (Sanchez-Rexach *et al.*, 2020; Yaragatti and Patnaik, 2020). New plant-based and polymer-based composite materials are being developed for AM (Li *et al.*, 2020; Andrew and Dhakal, 2022; Fico *et al.*, 2022; Acanfora, Zarrelli and Riccio, 2023; Doodi and Gunji, 2023). These materials can respond to external stimulus to deliver autonomous and shape-morphing characteristics, also known as 4D printing (Kuang *et al.*, 2019; Gauss, Pickering and Muthe, 2021; Khalid *et al.*, 2022). In addition to new material developments, recent commercial machines enabled multi-color 3D printing for more versatile and visually appealing prints.

In the field of regenerative medicine in particular, bioprinting has made great strides with the 3D printing of living tissues and organs using specialized bioinks and cell cultures (Gungor-Ozkerim *et al.*, 2018). Shape-memory polymer fibers found many applications as biomedical scaffolds, drug carriers, self-healing, smart textiles, tissues constructs, soft robotics, sensors, and energy harvesting devices (Khalid *et al.*, 2022; Wang *et al.*, 2022). These developments are furthering the potential of the technology beyond personalized implants already well-established in orthopedic, dental and hearing aid applications (Fu and Körner, 2022; Palmquist *et al.*, 2023).

Since AM starts from a digital model of the part to be produced, AM and digitalization are closely interconnected. Machine Learning (ML), Artificial Intelligence (AI), Internet of Things (IoT) and other data-driven technologies strengthen the sustainability of AM through design optimization, defect detection, process modelling, monitoring and control (Li and Yeo, 2021; Qin *et al.*, 2022; Park *et al.*, 2023). Developments in post-processing techniques were also instrumental in advancing AM, enabling advanced surface finishing, such as polishing and coating, and improved the quality and aesthetics of AM-produced parts (Laleh *et al.*, 2023).

Digital threads can capture data throughout the product life cycle and improve the manufacturing process (Mies, Marsden and Warde, 2016). These data-driven technologies can, for example, combine digital tools, such as AM and big data analytics, reveal the relation between sustainable performance and AM parameters; for example, optimize AM parameters to improve part quality and reduce energy consumption (Majeed *et al.*, 2021). In another study, customized kayaks were produced using a product lifecycle management (PLM) system which included a CO_2 model and life cycle assessment (LCA) to estimate life cycle impacts and provide feedback to the customers (Bonham *et al.*, 2020). Through the product life cycle information generated by the PLM platform, more holistic decisions can be made leading to more sustainable production (Bras, 2009).

Other technological innovations are pushing the boundaries of AM applications with the development of faster processes, such as CLIP and HSS, and large-scale 3D printers for aggregate materials (mostly concrete), metals or polymers. For example, robotic arms and gantry systems are used to fabricate buildings, infrastructure components, and even whole vehicle structures. While these applications remain largely experimental, they hold the promise to automate traditionally manual construction processes and to increase the speed and scale of AM builds (Pessoa *et al.*, 2021).

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Conventional vs. additive manufacturing

During the Industrial Revolution started in the early 18th century and Second Industrial Revolution in the late 19th century, technological innovations transformed manufacturing from labor-intensive craft production to machine-driven mass production. Many of the processes characterizing these manufacturing paradigms are subtractive in nature, whereby objects are created by removing material from a solid block until the desired shape is obtained. Other approaches to manufacturing include casting, pressing and joining. Some complex geometries and internal features are challenging or impossible to create using such conventional manufacturing methods but can be produced with AM. For instance, injection molds with cooling channels can be produced with PBF-LB or BJT to enhance process efficiency, reduce cycle times, prevent warping and other defects for the molded plastic parts. Lightweight designs, optimized geometries and intricate lattice structures produced from metal alloys through PBF-LB or PBF-EB can create components impossible to manufacture with machining or forging techniques. The design freedom enabled by AM can integrate multiple functions into a single component, leading to improved performance through weight reduction, enhanced fuel efficiency, superior strength, and structural integrity.

A key advantage of AM is in its intrinsically material efficiency due to its subtractive nature. But the impact of AM compared to conventional manufacturing also goes beyond the process itself and extends to the whole supply chain and product life cycle (Despeisse *et al.*, 2017; Peng *et al.*, 2018; Rinaldi *et al.*, 2021). As a consequence, the economic benefits of AM can be unclear and challenging to assess (Machado *et al.*, 2019; Niaki, Torabi and Nonino, 2019). Examples of AM environmental impact evaluation methods include life cycle assessment (Faludi *et al.*, 2015) and product circularity assessment (Angioletti, Despeisse and Rocca, 2017).

While AM is often contrasted to conventional manufacturing, some technologies are blurring the line between manufacturing process categories. For example, hybrid AM processes combine different AM technologies or integrate metal powder bed fusion with milling or machining operations for post-processing (Strong *et al.*, 2018). In addition, multi-material AM (Sealy *et al.*, 2018) allows the simultaneous or sequential deposition of different materials to create multi-component structures or incorporate dissolvable support structures, challenging existing process categorization and definitions. As innovative manufacturing technologies are developed through hybridization and customization, their unconventional nature can become more difficult to fit neatly into existing categorizations, such as continuous liquid interface production (CLIP), digital light synthesis (DLS) or bioprinting techniques. There are other processes not standardized yet, such as some spraying processes not using an energy source for melting or binding the material (e.g., cold spray). Nevertheless, standardization efforts and collaboration within the AM community help establish common terminology and frameworks to better understand the unique features and capabilities of different manufacturing technologies (Mani, Lyons and Gupta, 2014; Martínez-García, Monzón and Paz, 2021).

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Sustainability implications

Numerous studies have explored the sustainability implications of AM and provided comprehensive reviews of its applications and resulting benefits (Huang *et al.*, 2013; Mani, Lyons and Gupta, 2014; Chen *et al.*, 2015; Ghobadian *et al.*, 2020; Javaid *et al.*, 2021). Famous industrial cases have often been used to demonstrate the broad benefits of AM on process and product performance (see **side box B**). Other reviews highlighted mostly economic motivation for AM adoption, but also environmental and social advantages (Niaki, Torabi and Nonino, 2019; Priarone *et al.*, 2020). Finally, some studies focused on environmental sustainability as a core value created by this technology (Bourhis *et al.*, 2013; Ford and Despeisse, 2016; Kellens *et al.*, 2017; Colorado, Velásquez and Monteiro, 2020).

The social dimension of AM has been less well explored and relates to general working conditions in manufacturing. This includes occupational health and safety, employment, and employee empowerment (Chen *et al.*, 2015; Ghobadian *et al.*, 2020). Broad social sustainability benefits across the value chain include customer value, collaboration and co-creation, quality of life, and better service (Kohtala, 2015; Ghobadian *et al.*, 2020; Naghshineh *et al.*, 2021).

This section discusses the known advantages and drawbacks of AM, covering all stages of the product life cycle as well as implications for a broad set of stakeholders beyond the manufacturing system itself. The sustainability implications of AM cover many complex and overlapping issues which can be broadly categorized as shown in Figure 3, including some of the barriers to adoption discussed in the next section. These include such as customization/personalization (on-demand production), material and energy consumption, management of process waste and chemicals, process optimization and quality insurance, supply chain management, product performance and durability, social and ethical impacts, and life cycle considerations during production to achieve an eco-efficient and circular economy (Despeisse and Acerbi, 2022). The different categories of pros and cons are mapped against examples of applications in various sectors in Table 2.

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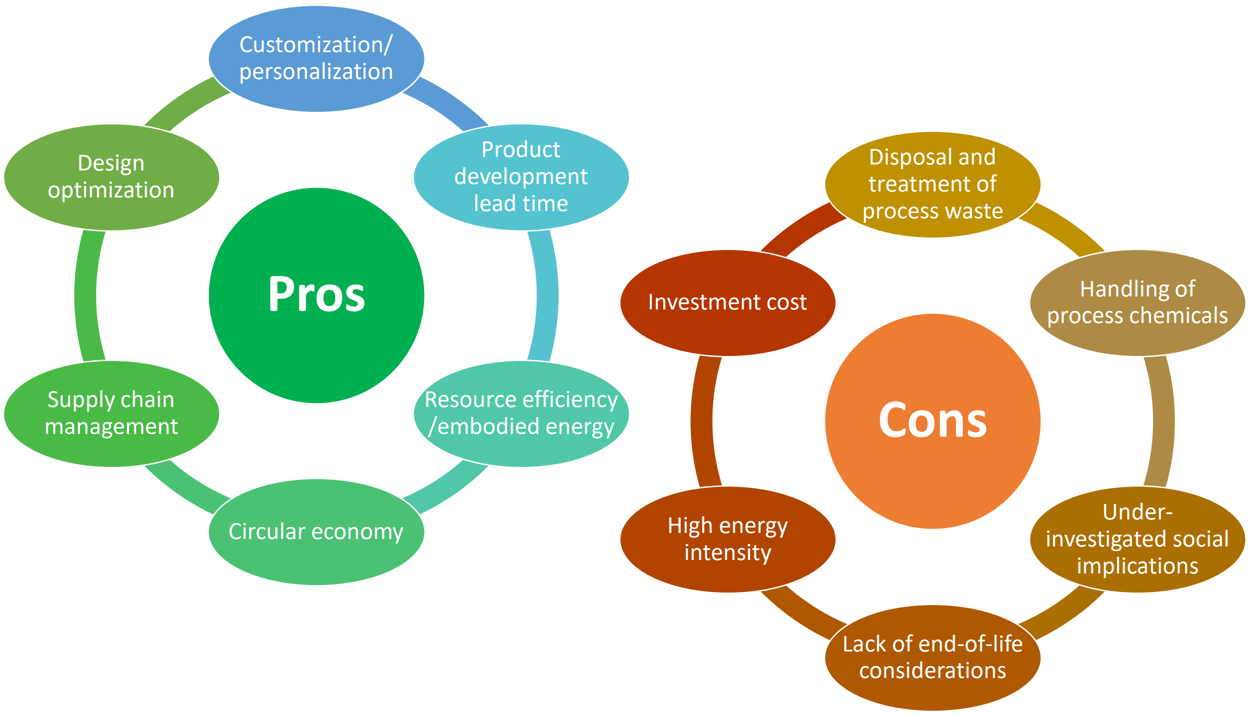

Figure 3. Pros and cons of AM technologies discussed in this section and the next on barriers to adoption.

Table 2. Examples of applications with their pros and cons.

Sector (material)	Description	Pros	Cons
Fashion (plastic)	Adidas Futurecraft 4D shoe midsole produced using DLS from a proprietary resin developed by Carbon	Customization/personalization, material efficiency and lightweight design	Energy consumption, material selection and recycling
Automotive (metal)	General Motors Chevrolet Corvette's engine bracket and other automotive components from metal alloys	Lightweight, material efficiency, consolidated component and product durability	Energy consumption, raw material production, end-of-life considerations
Automotive (ceramics)	Ceramic exhaust manifold coating (spraying/direct deposition)	High-temperature resistance, product durability, improved efficiency, weight reduction	Energy consumption, material sourcing and processing, end-of-life considerations
Medical applications (various materials)	Patient-specific implants, such as titanium cranial implants, prosthetics or orthopedic implants	Customization/personalization, material efficiency, lightweight to improve patient comfort, reduce the strain on surrounding tissues, and potentially contribute to improved recovery and rehabilitation.	Energy consumption, raw material production, waste management

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Famous AM industrial cases (side box B)

GE Aviation

GE Aviation, a subsidiary of General Electric, incorporates AM in the manufacturing and remanufacturing of aircraft engine components. An iconic example of a product made with AM is the GE Aviation fuel nozzle for aircraft engines. This component is produced using powder bed fusion - laser beam (PBF-LB) and is known for its complex internal geometry. AM enables the production of lightweight structures with optimized designs. The intricate internal channels in the fuel nozzle achieved through AM enabled overall weight reduction of the engine, improved combustion efficiency, and improved overall engine performance, leading to reduced emissions and lower environmental impact during aircraft operation. In addition, AM allows for precise and material-efficient manufacturing as only the necessary amount of material is deposited, minimizing process waste and optimizing resource utilization.

In addition, GE Aviation also leveraged AM technologies, to refurbish and repair high-value parts, such as turbine blades or fuel nozzles. Remanufacturing reduces the need for new part production, preserving valuable raw materials and reducing resource consumption, as well as reduces the generation of waste and limits the environmental impact associated with disposal.

Caterpillar

A well-known example of AM for a more circular economy is the application of AM for remanufacturing at Caterpillar, a leading manufacturer of construction and mining equipment. The company offers remanufacturing services for engine components, such as cylinder heads or fuel system parts, to extend the useful life of its products and reduce the need for new part production, thereby conserving resources. In addition, by restoring used components, Caterpillar reduces waste and the environmental impact associated with the disposal of worn-out parts. Finally, remanufacturing locally reduces the energy consumption and carbon emissions associated with transporting and manufacturing new parts.

Siemens

Siemens has successfully introduced AM in repair and manufacturing of burners for their industrial gas turbines. This allowed Siemens to decrease the delivery time for 30 burners from 44 to 4 weeks by cutting off only the damaged tip and manufacturing it by AM instead of cutting by half the mixing tube and welding a new one. Siemens has nowadays introduced powder bed AM to directly manufacture the top part of the burner in one piece, which allowed them to decrease number of components from 13 to 1, fully avoid welding (18 welds in case of conventional manufacturing) and hence significantly cut time and costs for quality inspection, to decrease the weight from 4.5 to 3.6 kg and to reduce manufacturing time from 20 to 3 weeks. Such pronounced decrease in lead time has a significant impact on cost saving as downtime for gas turbine can cost up to million EUR per day, depending on site and location. Moreover, there is improved functionality for cooling due to the lattice structure, possible to produce only by AM, further improving functionality and decreasing fuel consumption. AM is also considered as enabler for development of sustainable energy systems using hydrogen fueled gas turbines.

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Advantages (pros)

A key advantage offered by AM is the ability to efficiently print customized and optimized products without a need for special tooling. As a result, AM has been recognized as one of the most promising technologies to realize ecodesign principles (Peng *et al.*, 2018) as it supports eco-innovation with significantly shorter time and costs for prototyping (Niaki, Torabi and Nonino, 2019). The design freedom enabled by AM can create complex geometries and lightweight structures for optimal material usage and can lead to superior product performance (Tang, Mak and Zhao, 2016). AM makes product design changes easier to achieve, directly affecting the time-to-market of new products.

Compared to traditional subtractive manufacturing processes which generate significant material waste, AM is highly material-efficient as it deposits only the amount of materials required for the specific design. In the case of powder bed fusion, much of the unused powder can be sieved and reused. Topology optimization is a technique aimed at minimizing the material used in a product while ensuring the mechanical properties satisfactory (Bendsøe and Sigmund, 2004). It seeks to find the optimal structural layout considering applied loads, support conditions, build volume, and other design constraints. Although this concept has existed for a long time, conventional manufacturing techniques were unable to accommodate the manufacturing of complex products. Topology optimization in AM enables the manufacturing of lightweight components with less material consumption while meeting minimum mechanical requirements (Sauerwein *et al.*, 2019; Li and Yeo, 2021). Continuous improvement of AM technologies allows to further increase material efficiency through higher material reuse rate in powder-bed technologies and through improved process control (Gruber *et al.*, 2019; Raza *et al.*, 2021).

While AM is generally considered as more energy-intensive compared to traditional manufacturing for certain applications (Yoon *et al.*, 2014), it is essential to consider the energy requirements of the entire lifecycle. Embodied energy analysis should include material production and preparation, machine utilization, post-processing (Baumers *et al.*, 2011, 2013; Faludi *et al.*, 2015), but also product usage and end of life (Peng *et al.*, 2018). In many automotive and aerospace applications, the lightweight components enabled by AM result in significant energy savings during the vehicles' useful life, largely offsetting the additional energy consumed during their production.

AM also has numerous supply chain implications (Afshari, Searcy and Jaber, 2020; Kunovjanek, Knofius and Reiner, 2020; Rinaldi *et al.*, 2021), especially for on-demand manufacturing. Materials and processes can be tailored for circular economy (Colorado, Velásquez and Monteiro, 2020). For example, focusing on source materials from renewable feedstock for green AM (Sanchez-Rexach *et al.*, 2020) or using recycled or biodegradable filament (Pakkanen *et al.*, 2017). Similarly for metal AM, the use of recycled and reused feedstock can reduce the reliance on virgin materials (Cordova *et al.*, 2020) as well as ensuring that the materials used are recyclable at the end of the product's life.

In addition, since AM enables the production of optimized designs with simpler assemblies (fewer components) and superior product performance (Sauerwein *et al.*, 2019), it can result in more durable parts better suited to the specific requirements, in line with circular economy principles (Despeisse *et al.*, 2017; Monteiro *et al.*, 2022).

Traditionally, when a part in a complex system becomes damaged or worn out, the entire system often needs to be replaced or repaired, which can result in downtime, high costs, and increased waste. Producing spare parts locally and on-demand can eliminate the need for excessive inventory, reduce

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unused or obsolete parts, as well as reduce lead time, transportation costs and emissions (Knofius, van der Heijden and Zijm, 2016; Kunovjanek, Knofius and Reiner, 2020).

Additionally, personalized and customized designs enabled by AM add a psychological value to the product. Users tend to develop a stronger emotional connection to personalized products, leading to better maintenance and extended useful life, delaying product obsolescence and disposal (Diegel *et al.*, 2010; Sauerwein *et al.*, 2019).

Drawbacks (cons)

The sustainability impacts of AM vary depending on the application, specific technology used, material feedstock, scale of production, and various life cycle considerations. It is essential to note that the technological limitations and challenges discussed in this section may be short lived as AM technologies and their supporting ecosystems are progressing rapidly. For example, five years ago in Europe, Al-alloy parts would normally be machined and imported from Asia due to high Al-feedstock prices. These same parts are now considered for local production using AM because additional factors are changing the business case, such as geopolitical or environmental reasons. Similar trends can be observed for Ni-alloys, Fe-alloys, etc.

The sourcing of AM materials remains a major concern in general as they involve resource-intensive mining, refining, and processing which can lead to habitat destruction, resource depletion, and pollution. Some advanced AM processes require specialized materials and additives that may have their own social and environmental implications. For example, AM for jewelry relies on sensitive materials which must be ethically sources to be considered sustainable. The powders used in metal AM, require particularly energy-intensive processing. The environmental impact associated with material production and transportation should be considered. When selecting AM feedstock, it is essential to consider the footprint of different material alternatives and potential tradeoffs between beginning, middle and end of life phases of the product life cycle.

Although AM can reduce material waste compared to traditional manufacturing, there is still waste generated during the process, especially when a build requires support structures (Strano *et al.*, 2013). Unused powders, support structures, failed prints, and post-processing residues can contribute to significant amounts of waste if circular strategies are not in place. The disposal of process waste, particularly when not easily recyclable, can result in negative environmental impacts. In addition, AM can produce complex products with mixed materials that may be challenging to disassemble, repair and recycle at the end of the product life cycle. This can hinder the implementation of circular strategies and contribute to waste management challenges.

Another example of negative impacts related to the linear economy is the over-use of AM to produce low-value, disposable or single-use plastic items through fused deposition modelling, contributing to unnecessary energy consumption and waste (Suárez and Domínguez, 2020). Educating AM users is essential to prevent and mitigate the negative impacts of the technology. It is critical to focus AM efforts on sustainable and responsible applications with full life cycle considerations to produce durable, reusable, or recyclable products. Strategies to prevent and mitigate environmental impact include optimizing processes for material and energy efficiency, using environmentally friendly material alternatives, implementing responsible waste management strategies for AM process waste and chemicals, ensuring the long-term durability and performance of products, and integrating sustainable

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design principles into product development to minimize environmental impacts across the entire product life cycle. Efforts must be made to address these environmental concerns through energy efficiency, material selection, recycling methods, and the development of more sustainable AM processes.

Regarding resource intensity, advanced manufacturing and digitalization consume more resources and energy, as well as generate more electronic waste (Chen, Despeisse and Johansson, 2020). For example, AI can optimize AM design and processes, but AI model training entails an increased carbon footprint from the supporting IT infrastructure (Nishant, Kennedy and Corbett, 2020). Although digitalization can positively impact the sustainability of AM (Li and Yeo, 2021), increased negative impacts should be carefully considered to avoid, reduce or mitigate them. The challenges for AM are similar to other manufacturing technologies and include the environmental impacts of material production, energy requirements, process waste and process chemicals, and the overall life cycle considerations of AM-produced parts. Additional energy demands beyond the manufacturing process are often overlooked but should be considered more systematically as digitalization can shift impacts from one life cycle stage to another (reduced manufacturing process energy through optimization but increased energy consumption of the overall manufacturing and IT systems).

While the AM process is typically more energy demanding than conventional manufacturing to produce a single component, it is important to consider the total life cycle energy for producing this component (see embodied energy discussed in the previous subsection). The energy requirements of AM processes can vary depending on the technology, the machine capacity used, the size and complexity of the printed object, and the materials involved (Baumers *et al.*, 2011; Faludi *et al.*, 2015; Qin *et al.*, 2022). AM processes consume a significant amount of energy per component compared to mass production using traditional manufacturing methods, such as injection molding for plastic parts or machining and casting for metal parts. The main factors determining AM process energy are strongly correlated: manufacturing time, largely determined by the built height which depends on the part geometry and orientation, as demonstrated for SLS technologies (Baumers *et al.*, 2011). If powered by non-renewable or high-carbon sources, such energy-intensive processes, contribute to greenhouse gas emissions and other environmental impacts associated with energy generation.

From a health and safety perspective, AM processes involving high-temperature melting or the use of certain materials can release harmful emissions requiring appropriate ventilation or filtration systems to prevent or mitigate their environmental and health impacts (Dobrzyńska *et al.*, 2021). For example, some AM processes use binders, solvents, or surface treatments for powder preparation, post-processing, or finishing (Bours et al. 2017). The improper management or disposal of these chemicals can result in environmental contamination, pollution, and harm to ecosystems if not handled with appropriate care.

From social sustainability viewpoint, combining AM with digitalization enables automated and remote production which has both positive and negative impacts (Naghshineh *et al.*, 2021). On the one hand, remote production can empower local communities and enable proximity between suppliers, manufacturers, and customers. Further, operators and engineers may have safer work conditions due to reduced exposure to hazards related to manufacturing processes. On the other hand, additional care should be placed on employment structure and workers' wellbeing as automation can reduce the demand for labor and remote production might isolate the workers from their workplace.

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Other concerns include IP, liability and regulatory issues when AM is used by a broader landscape of legal players, such as sub-suppliers, micro-sellers or individuals producing parts of varying quality leading to defects, product failure and other safety concerns. Illegal applications of the technology have also emerged; e.g., reverse engineering, counterfeiting and theft causing IP infringement and security problems (Gupta *et al.*, 2020). For instance, spoofing face recognition with 3D masks (Erdogmus and Marcel, 2014), unauthorized manufacturing of security key or firearms are among the well-known examples (Adu-Amankwa and Daly, 2023). This becomes more intricate as IP law operates differently in different national jurisdictions.

Barriers to adoption and technical challenges

While AM offers numerous sustainability benefits, there are several reasons why its adoption is not more widespread today (Thomas-Seale *et al.*, 2018). Based on a 2021 survey by Hubs[1], the primary obstacles to the democratization of AM are cost, quality, limited expertise, and material choice. These challenges impede in-house AM manufacturing, as companies encounter limitations in terms of purchasing an AM machine that is restricted in terms of material compatibility, build volume, and batch size. Moreover, additional expenses for service and maintenance further compound these limitations. This section discusses some of the barriers to adoption hindering the widespread of AM for industrial implications based on the current state of knowledge and practice. Similar to the previous section on *Drawbacks*, these limitations are constantly being pushed through AM research and development.

Material and process limitations

Despite advances in material development, the range of materials accessible for AM remains limited. New materials and the optimization of their properties specifically for AM processes continue to pose challenges, thereby hindering the broader adoption of AM across various industries (Stavropoulos *et al.*, 2023). In addition, not all available materials can be utilized with all types of printers. Each printer relies on a specific set of materials, further restricting the material options for AM (Gao *et al.*, 2015; Ngo *et al.*, 2018).

The majority of AM processes involve printing within a confined build chamber. As a result, the size of the parts is restricted to the capacity of the chamber, limiting the volume that can be produced in each printing cycle (Page, Yang and Zhao, 2019). Furthermore, unlike traditional manufacturing, the batch size in AM is significantly smaller. Although multiple parts can be manufactured in a single printing round, the overall number of parts remains limited (Yang *et al.*, 2020). Moreover, when multiple parts are printed on a single plate, there is an increased risk of failure. If any issues arise during the printing process, it can potentially affect the entire batch of parts.

When compared to traditional manufacturing, AM introduces a multitude of variables that require careful consideration. One such variable is the direct correlation between print quality and the setup and condition of the printing process. This includes factors such as feed material properties, spreading

[1] Report accessible online:
https://f.hubspotusercontent10.net/hubfs/4075618/Additive%20manufacturing%20trend%20report%202021.pdf

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mechanism, and printing speed, all of which significantly impact the outcome (Gibson et al, 2015). However, it is important to note that while industrial process parameters for defect-free fabrication of certain materials may be available in some cases, they may not be readily accessible for all materials or AM processes.

The automated nature of AM brings about certain constraints, such as the fixed build time and limited ability to adjust the geometry once the printing process begins. Consequently, having well-informed and precise Design for Additive Manufacturing (DfAM) processes becomes critical. By incorporating extensive design knowledge, considering manufacturing and material constraints during design and development, and utilizing process simulation, it becomes possible to identify and mitigate potential build failures prior to the start of manufacturing. Although in-process monitoring can detect failures during the build, detecting design errors at that stage proves to be inefficient in terms of time and cost (Thomas-Seale *et al.*, 2018).

Production cost and speed
Although AM has shown advantages in low-volume production, it faces challenges in attaining economies of scale comparable to traditional manufacturing methods such as injection molding. This is primarily due to the higher cost and slower speed associated with AM (Ngo, 2018). The longer cycle times required for AM processes can result in increased costs, making it less competitive for mass production compared to traditional methods (Gao *et al.*, 2015).

However, there are specific situations where the advantages of AM outweigh its slower cycle times. These instances involve consolidating parts, reducing material waste, and meeting the demand for customized geometry. By leveraging AM's capabilities, such as the ability to create complex shapes and designs, it is possible to achieve cost-effective large-volume production (Gao *et al.*, 2015).

To facilitate the industrialization of AM, efforts have been made to introduce low-cost 3D printing systems targeting entry-level users and personal use. These systems predominantly employ FDM technology due to its widespread availability and ease of implementation. However, the future may bring advancements in droplet-based technology, which is expected to become more prevalent as major printer manufacturers determine that the market can sustain the necessary capital investment (Campbell, Bourell and Gibson, 2012).

Quality and process monitoring
Inconsistent quality and anisotropic mechanical properties are between the main barriers for broader industrial adoption of the metal additive manufacturing (Gao *et al.*, 2015). Parameter variation within the build, including process-based (laser and scanning related parameters, processing gas, layer thickness, etc.) and material-based (material type and powder properties) directly affects material quality by impacting melt flow stability, material porosity, and surface roughness (Thomas-Seale *et al.*, 2018; Leicht *et al.*, 2020). These variations make quality control and traceability difficult, however recent developments in quality control processes are addressing this issue with a variety of in-situ monitoring tools; e.g., high-resolution high-speed optical cameras for powder bed monitoring as well as defect formation in powder-bed system. Variety of more dedicated systems, such as optical tomography and melt pool monitoring in PBF-LB/M (Schwerz *et al.*, 2021) and possibility of using low-energy secondary electrons and high-energy back scattered electrons for process monitoring in PBF-EB (Fu and Körner, 2022), is available on the market. Successful adoption of dedicated quality assurance systems can

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support the widespread of AM for industrial applications. Effective in-process monitoring and the establishment of process-structure-property relationships integrated with computer-aided design (CAD) tools are essential for detecting and predicting defects, improving final designs, and ensuring consistent quality (Ngo *et al.*, 2018).

Post-processing

Post-processing is an integral part of AM, as it ensures that the parts produced are ready for use. While the ideal scenario is minimal manual intervention after printing, the reality is that most AM parts require significant post-processing to achieve the desired quality and functionality of the final AM parts (Gibson, Rosen and Stucker, 2015a). This includes tasks such as removing excess build material or support structures, heat treatment and hot isostatic pressing to reach necessary microstructure and mechanical properties, chemical and electrochemical treatment to improve surface quality, etc. Further, machining can be performed to increase dimensional accuracy and surface quality.

Post-processing in AM is not only time-consuming but also entails significant costs. This cost encompasses various steps, including detaching it from the build platform, removing support materials, heat-treating the part, and achieving an acceptable surface finish. According to the Wohlers Report, up to 70% of the total part cost can be attributed to pre- and post-processing activities. While AM offers the advantage of manufacturing complex structures, this complexity contributes to the challenges, increased costs, and time required for post-processing (Diegel, Nordin and Motte, 2019).

Interoperability

When integrating new methods, considering interoperability with existing systems is crucial for successful implementation (Gericke *et al.*, 2020). However, currently AM is on the shop floor (Stavropoulos *et al.*, 2018) and AM design methods are insufficiently integrated with the digital infrastructure in place (Mallalieu *et al.*, 2022). Further, incompatibility in file formats, particularly with CAD, creates a bottleneck for expanding design and materials in AM. The subtractive nature of CAD conflicts with the additive approach of AM, and existing CAD software lacks specialization for AM, limiting its ability to handle graded materials, lattice generation, and porosity modeling. Combining software or add-ons can partially alleviate this limitation and enable the integration of solid and porous structures in components (Thomas-Seale *et al.*, 2018).

However, CAD files cannot be directly used for printing and require tessellation for improved accuracy and reduced defects (Ngo *et al.*, 2018). Although the common format STL is used for CAD file transfer, it results in information loss, including design features and modeling history (Mallalieu *et al.*, 2022). Editing issues also arise, as any design changes must be made in the original CAD file rather than the STL format (Gibson, Rosen and Stucker, 2015b). To address compatibility and preserve material and manufacturing parameters, the industry is shifting from STL to the 3D Manufacturing Format (3MF) (Thomas-Seale *et al.*, 2018). This transition aims to enhance interoperability; however, challenges remain, such as difficulty in recognizing holes or retaining fully enclosed surfaces when converting files, which calls for further research.

AM standardization and intellectual property

Establishing material, process, calibration, testing, and file format standards is crucial to ensure part quality, repeatability, and consistency across builds and machines, but efforts to address this deficit have

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only recently begun (Thomas-Seale *et al.*, 2018). The diverse range of machines, materials, and processes in AM makes developing a uniform standard challenging. It is more critical to have a reliable standard when it comes to the safety critical parts (e.g. in commercial aircrafts) (Mellor, Hao and Zhang, 2014). Furthermore, the financial interests of machine manufacturers in providing custom consumables and spares can compete against the need for standardization, hindering progress in this area (Gao *et al.*, 2015).

In addition to standardization challenges, intellectual property issues arise as the 3D printing marketplaces and downloadable open-source projects challenge existing legal and regulatory frameworks. This poses a fundamental shift in the way design patents are filed and protected. To safeguard the intellectual property of CAD models, researchers have explored methods such as embedding specific 3D information into the spectrum domain and utilizing internal structures visible only under terahertz wave, aiming to enhance encryption and protection (Gao *et al.*, 2015). The AM industry and research institutions face significant hurdles as they work towards consensus on standards and address intellectual property concerns in this evolving domain.

Knowledge gap and decision support

AM has fundamental differences with traditional manufacturing, making it crucial to teach and communicate dissimilarities and advantages clearly. From a technical perspective, it is important to acknowledge that effectively utilizing AM necessitates proficiency in infrastructure, materials supply, specialized software, and substantial knowledge in design (Rylands *et al.*, 2016) From the infrastructure standpoint, companies must understand how the implementation of AM would impact the current manufacturing process (Hajali *et al.*, 2023), including production planning and quality control (Mellor, Hao and Zhang, 2014).

Furthermore, incorporating AM requires engineers to acquire new skillsets (Despeisse and Minshall, 2017). For instance, not all the available software is compatible with AM, requiring the purchase and proficiency of new software tools. Additionally, traditional design guidelines are inadequate in the realm of AM, as its unique capabilities enable novel design possibilities. Design engineers need to familiarize themselves with AM-specific design rules and guidelines and incorporate them into their practices. While conventional manufacturing technologies limit design exploration to squared and cubic shapes, AM offers greater design freedom. It is vital to recognize that, although AM presents numerous advantages over conventional techniques, it does not eliminate constraints entirely but replaces them with AM-specific limitations (Borgue *et al.*, 2019).

Although AM excels in sectors like healthcare and aerospace, where customization and lightweight design are critical, other applications involve a tradeoff between traditional manufacturing and AM (Tian *et al.*, 2022). According to Tian et al. (2022), "AM with digital genes needs to improve the core competitiveness in terms of large-scale production efficiency, quality control and flexibility on the basis of maintaining the benefits of customization". Other factors further complicate the decision-making process, such as the energy consumption of AM compared to conventional manufacturing. Although AM may consume more energy, it utilizes less material to produce a part with comparable properties to those manufactured traditionally. Consequently, it is essential to take a holistic view of the product life cycle and consider it as one of the key criteria alongside others. Currently, there is no universally applicable standard or procedure to analyze the tradeoff between AM and traditional manufacturing.

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Existing approaches lack organization-specific adjustments and operationalizability (Foshammer *et al.*, 2022).

Therefore, understanding the changes, capabilities, and limitations of AM is crucial for its successful integration within a company. However, this integration can be hindered by the resource-intensive nature of AM. Currently, knowledge of AM is not routinely taught at the undergraduate level. As teaching programs get updated based on state-of-the-art knowledge and industry needs, AM as an engineering and technology management topic will become more integrated into various levels of education, facilitating its industrialization (Despeisse and Minshall, 2017; Thomas-Seale *et al.*, 2018).

Summary

AM is positioned as a key enabler for sustainable production due to its inherent characteristics connected to near-net shape manufacturing, resulting in high material efficiency, as well as individualized and flexible manufacturing of complex 3D shaped objects on-demand. In addition, feedstock materials can be either reused in case of metal or sourced sustainably, as in case of renewable bio-based polymers. Further economic and social benefits can be realized along the supply chain and life cycle of the materials and products, depending on the selected technology, material, and application. This article provides an overview of additive manufacturing developments and their potential sustainability benefits and challenges, along with concrete examples of different technologies and applications. The sustainability implications discussed are of high importance for AM technology management and development. However, it is important to note that the limitations, drawbacks, barriers and challenges presented may be short lived as technologies and their supporting ecosystems are being continuously improved through collaborative efforts across the AM community.

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