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ADDITIVE TECHNOLOGIES PROCESSES: AN EXTENSIVE STUDY

Abstract: *This paper examines various additive manufacturing technologies, highlighting their resources, material usage, waste generation, and environmental impacts, along with a detailed descriptions for each type of processes: Material Extrusion, Material Jetting, Directed Energy Deposition, Powder Bed Fusion, Sheet Lamination, Vat Photopolymerization, and Binder Jetting. A detailed comparison emphasizes the applications, materials, accuracy, cost, and sustainability aspects of each process. The findings underline the potential of AM to support sustainable manufacturing through eco-friendly initiatives, like Precious Plastic, while stressing the need for innovations in recycling, waste reduction, and eco-friendly design. This kind of open-source collaboration encourages communities across the globe to develop alternatives to the standard recycling systems.*

Key words: *Additive manufacturing, 3D printing, plastic materials, metal materials, sustainable manufacturing, manufacturing process.*

1. INTRODUCTION

Ever since the first commercial additive manufacturing application in 1987 [1], [2] 3D printing has diversified in many types of processes and started attracting a variety of materials to make parts for different industries [1] like design, engineering, manufacturing and tooling, aerospace, automotive, jewellery, tableware, coin manufacturing, art, architecture, buildings and construction, fashion and textile, musical instruments, health and food processing, film industry, marine applications etc.

Taking in account the fast and complex advancements in additive manufacturing, the issue of sustainability should be considered in the development of new parts. Based on 2030 targets imposed by the United Nations [3] and 2050 strategy from the European Union [4], all industries must adopt at least a climatic neutrality or reduce their carbon dioxide emissions by 2030.

The first steps into the circular economy strategy have been set by European Union through the Ecodesign for Sustainable Products Regulation [5] or ESPR, launched in July 2024, which sets a package of requirements for ecodesign. Some of the law's pillars are the recycling and upcycling of the products and increasing the recycled materials content in products [5]. In parallel, the United Nations environment programme, "Turning off the Tap" [6], proposes significant reduction in the usage of plastics. Their policies focus on 3 market shifts – Reuse, Recycle, Reorient & Diversity. Those shifts should impact the way people have access to reusable products, the methods of recycling the current plastic products and the promotion of alternatives to the plastic for the whole population.

Subsequent to those global strategies, additive manufacturing must adapt to these requirements and integrate into a circular economy approach in the future.

In this paper, each additive manufacturing process will be compared and evaluated based on the tools needed for printing and the materials used for the fabrication of parts. The complexity of the parts printed will be also assessed in the comparison, based on the features and volumes that can be achieved through a specific process. In addition, an economic criterion will be taken in account as a reference for investment in the manufacturing process. Lastly, an environmental impact review will be conducted based on the information gathered from the literature for each additive manufacturing process.

2. DEFINITION AND CLASSIFICATION

Firstly, it is important to understand what additive manufacturing (AM) means. Based on the ISO standard definition [7], "additive manufacturing is a process of joining materials to make parts from a 3D model, usually layer by layer, as opposed to subtractive manufacturing and formatting manufacturing methodologies". AM has multiple types of processes, based on the method applied for printing the layers and the state of the material used for printing. Additive manufacturing is separated into 7 categories [7], [8]: binder jetting (BJT), directed energy deposition (DED), material extrusion (MEX), material jetting (MJT), powder bed fusion (PBF), sheet lamination (SHL), vat photopolymerization (VPP).

Another classification is based on the state of the material used for the printing. Based on the state of the matter, there are 3 main categories [1]: liquid-based manufacturing, solid-based manufacturing, and powder-based manufacturing. Those 3 main categories influence the starting price for the raw material, the storing capacity or conditions for the materials and the operating constraints for each printing machine.

2.1. Material extrusion (MEX or FDM)

Material extrusion (MEX) or fused deposition modelling (FDM) is a 3D printing process that makes use of continuous filaments as a base material [1], [9]. The filament is delivered from a coil to a moving, heated printer extrusion head, referred to as an extruder. The hot substance is driven from the extruder's nozzle and positioned first on a preheated 3D printing platform for improved adherence. Once the first layer has been printed, the next step is to separate it from the nozzle and the platform, after which the second layer is deposited directly onto the expanding workpiece.

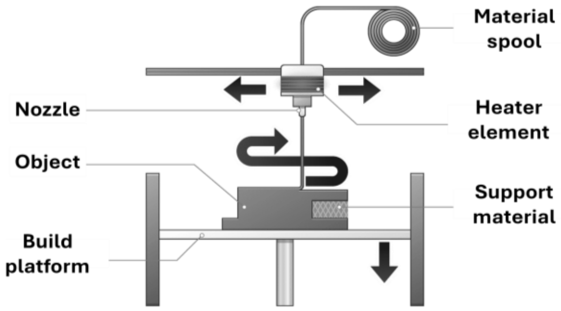

Fig. 1 FDM printing process [9]

The extruder head operates based on a program provided by a slicer software in the form of code [1]. Normally, this code contains the coordinates and movement needed to be made by the extruder head to complete each layer. One layer is placed on top of the prior layer until the item is fully manufactured [9].

Cartesian printers are used due to the 3 axes needed for printing instructions (similar to the Cartesian coordinate system XYZ). Lately, polar or delta system machines have been used for this type of printing, which can replace the Cartesian system architecture [9]. The printing diagram presented in Fig. 1.

For the FDM process, various materials that can be used from plastic, concrete, ceramics or composites to more organic materials like chocolate, for the culinary industry. Some of the most used materials in the industry are [9], [10], [11]: Acrylonitrile Butadiene Styrene (ABS), Polylactic Acid (PLA), PolyEthylene Terephthalate Glycol (PETG), High-Impact Polystyrene (HIPS), Thermoplastic PolyUrethane (TPU), PolyEther Ether Ketone (PEEK) or composites infused with carbon fibre, Kevlar or fiberglass.

Based on the characteristics of this printing process [12], [13], the products achieved through FDM will not be integrated in assemblies with a lot of mechanical stress and FDM is not recommended for critical components. MEX printers can manufacture most designs with the help of supports. Lately, FDM is used for basic proof-of-concept models or low-cost prototyping of simple parts.

2.2. Material Jetting (MJT, NPJ or DOD)

Material jetting (MJT) is a manufacturing technology that uses photopolymers, metals, or wax that harden when exposed to light or heat, allowing physical things to be constructed one layer at a time [14]. In theory, MJT dispenses a photopolymer from multiple tiny nozzles [14]. Then UV rays directly cure and solidify the layers.

Under the material jetting manufacturing process are covered 3 types of printing methods: Drop on Demand (DOD), PolyJet by Objet and NanoParticle Jetting (NPJ) by XJet [14]. Those 3 subprocesses differ based on the manufacturing steps and the material jetted.

The material jetting manufacturing technology enables many materials to be 3D printed inside the same object. This process also requires supports, which are printed during the construction from a dissolvable material (see DOD [14]). During the post-processing stage, the supports are removed from the finished part (by water cleaning, high temperatures or manually).

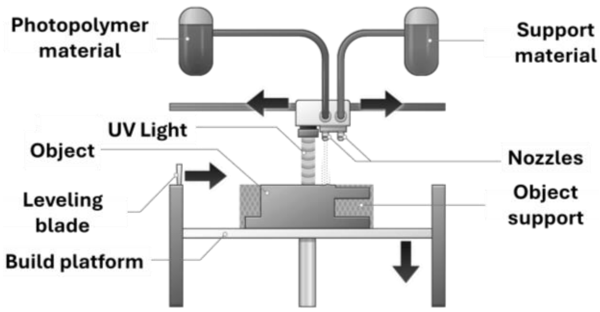

Fig. 2 MJT printing process [14]

Similar to MEX, this printing process uses Cartesian system printers. This technology has multiple uses, mostly in medical applications, tool-making for injection or thermoforming molds [15]. This allows the deposition of different materials or colours through the part, layer by layer. The whole printing diagram can be seen in Fig. 2.

For the MJT process, thermoset photopolymer resins are used. Those materials have limitations regarding physical properties as they are brittle, have low heat deflection and can creep. Materials like aluminium oxide, zirconia, stainless steel, different types of wax or UV-cured resins (with various colours and textures) are commonly used for this material jetting printing [15], [16]. The parts resulting from MJT [15], [16], [17] are flexible and have an opaque or transparent appearance. are flexible and have an opaque or transparent appearance. Through MJT complex geometries can be produced with some additional post-processing required for the metallic materials [16], [17].

2.3. Directed Energy Deposition (DED)

Directed Energy Deposition (DED) is an additive manufacturing process that produces components by melting materials and depositing them layer by layer, by a nozzle affixed to a multi-axis arm within an enclosed structure [11], [18]. This nozzle applies melted material onto the surface of the workpiece, where it hardens. While DED is similar to FDM, in this case the nozzle moves in various directions, incorporating up to five axes [18]. The whole printing diagram can be seen in Fig. 3.

The most known technologies from this type of AM are LENS Technology & Aerosol Jet Technology by Optomec, Electron Beam Additive Manufacturing (EBAM) by Sciaky, Laser Deposition Welding (LDW), and Hybrid Manufacturing by DMG MORI [18].

Aside from the capacity of LDW to create components from scratch (typically using a mill/turn CNC tool), the EBAM technology can also repair complex geometries (for example - propellers) [18]. Through a DED technology, Aerosol Jet Technology, Internet of Things can be integrated for building complex electrical components, using metal inks, dielectric pastes, semiconductors, and other functional materials. Most DED printers are industrial-grade equipment with large dimensions that will need a closed and regulated environment [18].

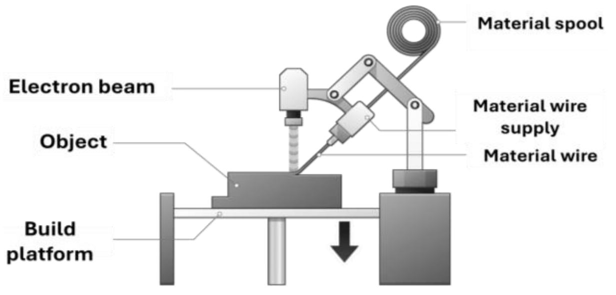

Fig. 3 DED printing process [18]

For the DED process metal powders or materials for wires are used. Some common examples of powders are [17], [18]: aluminium, copper, titanium, stainless steel, ceramics, tool steel, nickel alloys or other steel alloys.

Parts made by direct energy deposition [1], [17], [18], [19], [20] have complex geometries and present good mechanical properties. This type of manufacturing does not require any support structures which can minimise the quantity of material consumed. The downside of this manufacturing process consists in the closed chamber and post process heat treatment required for securing the printing.

2.4. Powder Bed Fusion (PBF)

Powder Bed Fusion (PBF) is an AM technology which creates parts by using a heat source, primarily either lasers or electron beams, to meld powder particles layer by layer into a solid object [21]. PBF offers multiple feasible technologies and materials, along with a high accuracy and a variety of complex geometries.

Under the Powder Bed Fusion manufacturing process are covered 4 types of printing methods [21]: Selective Laser Sintering (SLS), Selective Laser Melting (SLM) or Direct Metal Laser Sintering (DMLS), Electron Beam Melting (EBM) and Multi Jet Fusion (MJF). The first 3 technologies use lasers to create the layers and fuse them together, where MJF is based on heating each layer before fusing them, without the need of a laser. The whole printing diagram is available in Fig. 4.

This technology is used in different industries such as aerospace and defence, jewellery and dental industries, spare parts and prototypes or medical prosthetics.

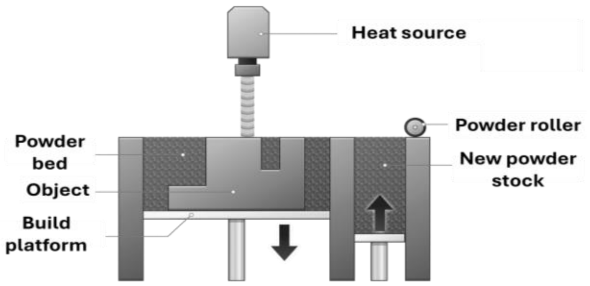

Fig. 4 PBF printing process [21]

For the PBF process there are various materials that can be used - plastics, rubber, metal alloys, composites. Some of the most used materials are [1], [11], [21], [22]: nylon and its composites, ceramics (alumina and zirconia), Polypropylene (PP), Thermoplastic polyurethane (TPU), alumide (a blend of aluminium powder and polyamide) or titanium-based alloys.

The main characteristic of PBF parts [1], [17], [23] is their durability. Similar to DED printing, supports are not used for the manufacturing, but special chambers and surface processing are needed to create functional parts.

2.5. Sheet Lamination (SHL or LOM)

Sheet Lamination (SHL) or Laminated Object Manufacturing (LOM) [24], [25] is a 3D printing process that involves superimposing many layers of foil-based material to create an item.

The most known technologies from this type of AM [24] are Composite Based Additive Manufacturing (CBAM) by Impossible Objects and Selective Lamination Composite Object Manufacturing (SLCOM) by EnvisionTEC. Ultrasonic Additive Manufacturing (UAM) is also a process that uses metal sheets to create parts by ultrasonic welding. The method uses a CNC machine to cut the unbound metal [25].

This type of AM process is based on layer-by-layer printing. The operator puts all of the sheets needed to complete the final item in the 3D printer, which utilizes them one at a time. Each sheet is removed from the stack, affixed to the preceding one, and then precisely sliced with a knife or laser. The operator can manually remove the leftover material. The accuracy of the final product is mostly determined by the thickness of the layered material utilized. Ergonomic research, topographical visualization, and architectural models for paper-made items are examples of LOM applications [24], [25]. The whole printing diagram can be seen in Fig. 5.

LOM uses a variety of materials, from paper [1], [24] to composites (reinforced with fibres) to thermoplastics. Thermoplastics and fibres enable cost-effective direct manufacturing of functional, lightweight technological components for the aerospace and automotive sectors [24]. Metals [1], [25] (for example - aluminium, copper, stainless steel, or titanium) and ceramics [26] are also used to make parts similar to the milled ones.

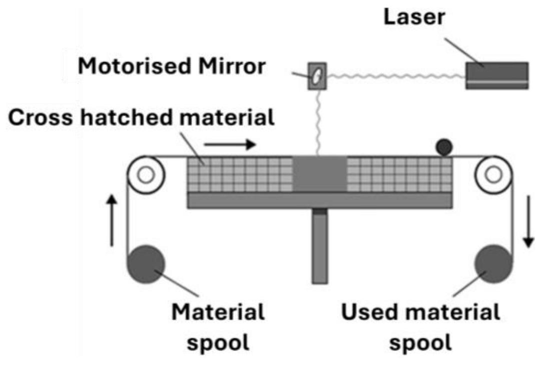

Fig. 5 LOM printing process [25]

Parts made by SHL [1], [24], [25], [26], [27], [28] are limited simple geometries due to the process and the layer thickness. This type of manufacturing does not require any support structure, but one limitation of the process comes also from the adhesive put between the layers which can fail in some climatic conditions.

2.6. Vat Photopolymerization (VPP)

Vat Photopolymerization (VPP) refers to a 3D printing method that uses a similar fundamental approach: a liquid photopolymer stored in a vat is selectively solidified using a heat source [1], [29]. Lasers and Digital Light Processing projectors, and even LCD screens are used for photopolymerizing materials. The last two are better alternatives to lasers due to their cost-effectiveness and exceptional resolution. Compared to lasers, one benefit of the last two methods is their capability to cure an entire layer of resin at once, whereas the laser must progressively illuminate the entire surface by tracing it [29]. The whole printing diagram can be seen in the Fig. 6.

Under the Powder Bed Fusion manufacturing process are covered 4 types of printing methods [29]: Stereolithography (SLA), Digital Light Processing (DLP), Continuous Liquid Interface Production (CLIP) by Carbon and Daylight Polymer Printing (DPP) by Photocentric.

The most known is Stereolithography (SLA) [29], due to the many uses in printing parts out of resin using ultraviolet light. This type of AM process is based on a layer-by-layer curing method. The light cures each resin layer before proceeding to the next layer [29].

Resin is the main material used for this type of AM. VPP can be used in medical applications and the resin used can be resistant to flames (non-flammable or high temperatures resistance). Through VPP [1], [11], [13], complex geometries can be produced with tight tolerances. Washing and post curing are also necessary in this case and supports removal should be also considered as an additional operation.

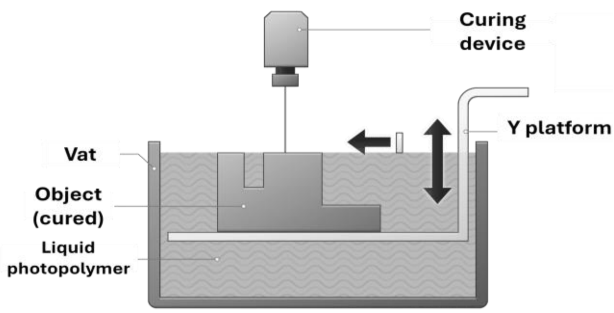

Fig. 6 VPP printing process [29]

2.7. Binder jetting (BJT)

Binder jetting is a 3D printing method that involves applying an adhesive binding agent onto thin layers of powdered materials [30]. In the binder jetting 3D printing workflow, the print head manoeuvres across the build platform, releasing binder droplets. Once a layer is fully printed, the powder bed shifts down, and the printer distributes another layer of powder over the build area.

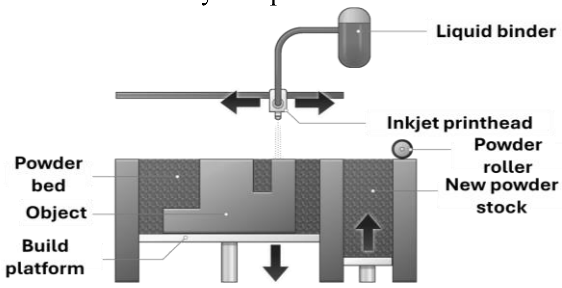

Fig. 7 BJT printing process [30]

This process continues, layer by layer until all components are finished. After completion, the printed parts need further post-processing to become usable. Typically, the operator introduces an infiltrated material - a cyanoacrylate adhesive for ceramics or bronze for metals [30] - to enhance the mechanical properties of the components. An alternative technique involves placing the workpiece in an oven while in its raw state to facilitate the sintering of the material grains. The whole printing diagram is presented in Fig. 7.

The most known technology from this type of AM is ColorJet Printing (CPJ) by 3D Systems [30], which uses coloured powders to create complex porous parts. ABS or PLA can also be used for this type of AM process [31]. This technology is useful for architectural models, packaging, toys, figurines, or even functional parts from metal for lower stresses [30]. The Sugar Lab used this type of 3D printing to create complex structures for the culinary industry based on water and sugar.

For the BJT process, various materials that can be used from sand to ceramic-based, such as glass or gypsum, or metal, such as stainless steel [1], [30]. This technology is useful for architectural models, packaging, toys, figurines, or even functional parts from metal for lower stresses [30].

BJT printed parts [1], [17], [30], [31], [32] can have complex geometries, but do not excel at mechanical resistance. Similar to DED printing, supports are not used for the manufacturing, but post-curing is needed to create the functional parts.

3. COMPARISON OF THE 7 AM PROCESSES

Considering all the information from the previous subchapters, Tables 1, 2 & 3 are made as a cross-comparison between the 7 processes. In those tables, 8 criteria have been considered for this study.

Depending on the type of application for 3D printing and based on the geometry criterion, we can assess that each type of AM process can fulfil a different role in manufacturing industry. For the prototyping phase of a project, where parts are produced in a very low quantity, FDM, MJT, PBF or BJT could be used to test the proof of concept. Those 4 processes allow quick manufacturing for a limited number of parts. For small series manufacturing, there are 2 main cases. If the parts are not put through a lot of strain, metal FDM, PBF or BJT technologies can be used to create components. In the second case, for complex parts which need to resist mechanical forces, DED or VPP can utilised. Another use of AM is for entertainment or hobby applications, where people print decorative parts or different small objects. Here, FDM, SLA or SHL might be the best options for beginners due to the ease of learning.

Depending on the printing accuracy required by the part, the AM technologies can be sorted in 2 ranges. If the print needs to have tight tolerances (complex geometries with functional intents), BJT, MJT, SLA, or LOM are the best in their bracket. If the part is noticeably big and the tolerances are also large, FDM or DED might serve the purpose of the print.

Based on the printing volumes for the current machines, DED has the biggest printing volume available, followed by VPP and BJT. The lowest printing volumes are for SLA, FDM, and LOM. It can be observed that the printing volumes are in close relation to the use of the printing machine (industrial or personal applications).

In corelation to the classification from the 2nd chapter, we can identify which AM process uses what type of material. Solid-based printing contains FDM and SHL, liquid-based is represented by MJT and VPP, and powder-based printing is DED, PBF, and BJT. The requirements for storing the raw material differ from a state to another. Each supplier of raw material suggests storing parameters, but generally, the material should be kept in a cool, dry environment, away from unnecessary UV exposure. For the solid materials, special mylar bags to avoid moisture and sunlight. For liquid or powder materials, canisters/boxes with sealing foam should keep the air or humidity reach the raw material.

The economic impact on the manufacturer is also an important point in choosing the right process. Based on the 5th and 6th lines, it can be concluded that FDM and paper based SHL are the lowest in terms of investment in raw materials and MJT or BJT the highest. For the machine investment, DED and PBF have the highest cost overall. The most affordable for a beginner in 3D printing are FDM or VPP/SLA, due to the low cost of maintenance.

Ultimately, the environmental impact will be represented through the last 2 lines. Regarding the post-processing step, this implies that some machines or agents are used to finish the part. The easiest way to finish a part is to sand it or to blast it with air or different abrasive material (see FDM, MJT, PBF or SLA). This process can generate dust or small particles of material that could be harmful to operator. This requires protective gear (masks, gloves etc.) and a dedicated chamber/room ventilated constantly. On the other hand, for the DED and PBF, special chambers are needed for the printing machine with inert gasses. This must be done in a controlled environment, which can keep the gases from escaping the printer perimeter and causing any damage to the environment.

Another process is the heat curing of the finished product to release the tensions in the material or to give the layers a better adhesion between them. Similar to the blasting procedure, protective gear (masks, gloves etc.) and a dedicated chamber are necessary. All those post-processing steps require energy and storage which can influence the carbon footprint for that AM technology.

Table 1

AM processes comparison – FDM & MJT

[1], [11], [12], [13], [15], [17], [26], [28]

CRITERIA	FDM	MJT
Geometry	Basic proof-of-concept	Flexible, complex geometries
Accuracy (mm)	From 0.2 to 1	From 0.1 to 0.2
Print volume (cm)	From 20X20X20 to 90X60X90	From 38X25X20 to 100X80X50
Material	Solid-based materials	Liquid-based materials
Average cost of the material / kg	\$50-\$150 (standard and industrial) & \$100-200 (supports)	From \$300 to \$1,000
Cost of the machine	From \$200 to \$4,000	Up to \$100,000
Waste and support management	The support can be soluble in water or can be easily removed	The support can be soluble in water, or it can easily melt
Other resources needed	Manual support removal, post-processing.	Additional post-processing required for some materials.

Table 2

AM processes comparison – DED & PBF

[1], [11], [13], [17], [18], [19], [20], [23], [26], [28]

CRITERIA	DED	PBF
Geometry	Complex structures with good resistance	Strong functional parts, prototypes
Accuracy (mm)	From 0.8 to 0.9	Around 0.13
Print volume (cm)	600X140X140	38.1X33X45.7 to 55X55X75
Material	Powder-based materials	Powder-based materials
Average cost of the material / kg	From \$100 to \$300	From \$100 to \$300
Cost of the machine	From \$100,000 to \$500,000	Below \$150,000 or up to millions of \$
Waste and support management	No support structure needed	No support structure needed
Other resources needed	Inert gasses needed to create a closed chamber and heat treatment	Inert gasses to create a closed chamber and particle blasting

Table 3

AM processes comparison – SHL, VPP & BJT

[1], [11], [13], [17], [24], [25], [26], [27], [28], [30], [31], [32]

CRITERIA	SHL/LOM	VPP/SLA	BJT
Geometry	Limitations for complex shapes	Highly detailed parts	Complex shapes, weak mechanical properties
Accuracy (mm)	From the thickness of the sheet (from 0.1)	From 0.1	From 0.05 to 0.3
Print volume (cm)	25.6X16.9X 15 to 76.2X60.9X 60.9	25X25X5 to 190X163X24 8	80X50X40 to 220X120X60
Material	Solid-based materials	Liquid-based materials	Powder-based materials
Average cost of the material / kg	Depends on the type of the sheet	\$100-\$200/L for most resins	From \$300 to \$990
Cost of the machine	From \$2,660 to \$16,130	From \$200 (hobby) to \$25,000 (industrial)	Around \$50,000
Waste and support management	No support structure needed	Manual removal of the supports	No support needed
Other resources needed	Post-processing for exterior, depends on the adhesive	Washing and post-curing	Post-curing and a polymer binder

Based on the information from the literature, most of the waste comes from supports or material left uncured. In the case of FDM or MJT, most of the supports will be considered waste. There are a few materials that can be soluble in water [33]: Polyvinyl alcohol (PVA), Butenediol vinyl alcohol copolymer (BVOH), Aquasys 120. Also some materials are soluble in organic solvents [33]: High Impact Polystyrene (HIPS), Polyvinyl butyral (PVB) or Acrylate TerPolymers. Those can help with disposing of left waste after printing and some of them are even biodegradable or recyclable [34], [35].

In comparison to conventional manufacturing processes where different tooling is required for obtaining the final product, AM has a smaller impact on environment due the consumption of resources [36]. Usually, there are multiple ways to mold plastic, through injection molding, blow molding, extrusion or thermoforming [37]. Most of them imply a high cost for equipment and operating, with long lead times. Any change in the design of the part will have a direct impact on the tool geometry and the parameters of the machine. Additive manufacturing can reduce the time and investment for small series production, especially when there are modifications to be done during the life of the product. Also employing recycled plastic in 3D printing presents significant ecological advantages, such as a possible decrease in waste and energy usage. Recycling and upcycling plastics can reduce carbon emissions up to 80% compared to processing and producing new plastics [38]. This opens up a new horizon for sustainable 3D printing, which can utilise recycled or biodegradable materials for day-to-day applications, for example as decorative household objects and promotes the concept of circular economy through new and emerging manufacturing.

One important mention of an open-source project is Precious Plastic [39], which was founded in 2013, as a possible solution for recycling day-to-day plastic items (bottles, containers, caps, plates, tubes etc.) through shredding the plastic items, then extruding the plastic chips into pellets or filaments. The generated materials could be used also for 3D printing, especially for FDM or PBF technologies. This community projects proposed a network of alternative recycling hubs to promote the reuse of plastic materials, the circular economy concept and to put in the spotlight new technologies or the creativity of the community, all on an open platform.

Currently there are articles on the possibility of using recycled materials like carbon fibre and recycled plastics and their mechanical properties [36]. Ceramics are also put into the spotlight due to the recyclability of glass [36] and the optical properties that can be added to the new parts. Besides metallic materials, various studies focus on recycled plastic materials in the additive manufacturing industry [36]. One well-known example is the use of PET in manufacturing new filaments for FDM printing [40]. Those filaments are later used for decorative applications and present fairly good mechanical properties at the first recycle process.

Besides this example, HDPE, low-density polyethylene (LDPE), polystyrene (PS), poly (vinyl chloride (PVC), and ABS and polycarbonate (PC) are recycled through sorting, shredding, cleaning and drying, melting, and extrusion into pellets or filaments [40].

4. OTHER IMPACT FACTORS ON ADDITIVE MANUFACTURING

Besides the points presented in the comparison, other factors are the parameters of printing, and the characteristics of the material used.

Each material used in 3D printing has its own set of characteristics (melting temperature, viscosity, chemical properties, filament size, layer thickness), which can influence the energy usage of the machine, the adhesion on the printing bed, and the concentration of volatile organic compounds emissions [36].

The parameters of the printing process are closely related to the geometry of the part and the capabilities of the printer. The printing speed, the base plate's temperature, the infill geometry, and density are key factors in the success of a manufacturing process [36].

In the end, the design of the part can influence the result of a printing cycle through the features available on the part and their correlation with the capabilities of the AM process and machine.

5. FUTURE DIRECTIONS AND CONCLUSION

Considering all the information gathered in this paper and the comparison done, the sustainability of additive manufacturing is codependent on the materials, procedure, and geometry of the part. The next step for AM in achieving sustainability is to look into recycling the current wasted (virgin) material into new filament or to reuse the printed parts in new assemblies. Another modification could be to rethink the design of the products in order to use fewer materials and supports.

In conclusion, additive manufacturing is starting to become an alternative to conventional manufacturing through its breakthroughs in medicine, industry, engineering, prototyping, and even packaging at a lower investment and maintenance.

REFERENCES

[1] Chua, C. K., Leong, K. F. (2017). *3D Printing And Additive Manufacturing: Principles And Applications (With Companion Media Pack)*, World Scientific Publishing, ISBN 978-981-3146-75-4, Singapore.

[2] Wohlers, T. et al. (2016). *History of Additive Manufacturing*. SSRN Electronic Journal, (April 2016), ISBN 978-0-9913332-2-6, doi:10.2139/SSRN.4474824.

[3] United Nations. (2015). *Transforming our world: the 2030 Agenda for Sustainable Development*., available at: *https://sdgs.un.org/2030agenda Accessed:* 2024-12-14.

[4] European Commission: Directorate-General for Climate Action. (2019). *Going climate-neutral by 2050 - A strategic long-term vision for a prosperous, modern, competitive and climate-neutral EU economy*, available at: *https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en Accessed:* 2024-12-14.

[5] European Commission (2024). *Ecodesign for Sustainable Products Regulation,* available at: *https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/ecodesign-sustainable-products-regulation_en#law Accessed:* 2025-01-08

[6] UNEP (2023). *Turning off the Tap: How the world can end plastic pollution and create a circular economy,* available at: *https://www.unep.org/resources/turning-off-tap-end-plastic-pollution-create-circular-economy Accessed*: 2025-01-08

[7] ISO. (2018). "*ISO/ASTM 52900 (en), Additive manufacturing - General principles - Terminology*, available at: *https://www.iso.org/obp/ui/#iso:std:iso-astm:52900:dis:ed-2:v1:en. Accessed*: 2024-12-30.

[8] Symmetry Electronics. (2022). *Defining Additive Manufacturing*, available at: *https://www.symmetryelectronics.com/blog/defining-additive-manufacturing Accessed*: 2025-01-04.

[9] Dassault Systèmes. *Material Extrusion, What is it and how does it work?,* available at: *https://www.3ds.com/make/guide/process/material-extrusion Accessed:* 2025-01-03

[10] Protolabs Network. *PETG 3D printing service | Custom PETG parts*, available at: *https://www.hubs.com/knowledge-base/fdm-3d-printing-materials-compared/#what-is-pet. Accessed*: 2025-01-04.

[11] Formlabs. *Guide to 3D Printing Materials: Types, Applications, and Properties*, available at: *https://formlabs.com/eu/blog/3d-printing-materials/ Accessed*: 2025-01-04.

[12] Protolabs Network. *What is FDM (fused deposition modeling) 3D printing?,* available at: *https://www.hubs.com/knowledge-base/what-is-fdm-3d-printing/ Accessed*: 2025-01-04.

[13] Formlabs. *How Much Does a 3D Printer Cost?*, available at: *https://formlabs.com/eu/blog/how-to-calculate-3d-printer-cost/ Accessed*: 2025-01-04.

[14] Dassault Systèmes. *Material Jetting, What is it and how does it work?,* available at: *https://www.3ds.com/make/guide/process/material-jetting Accessed*: 2025-01-04.

[15] Protolabs Network. What is Material Jetting 3D printing?, available at: *https://www.hubs.com/knowledge-base/introduction-material-jetting-3d-printing/#materials Accessed*: 2025-01-04.

[16] Xometry. *Material Jetting: Applications and Process*, available at: *https://www.xometry.com/resources/3d-printing/what-is-material-jetting/ Accessed*: 2025-01-03.

[17] Aniwaa. *What's the total cost of ownership for metal 3D printing?,* available at: *https://www.aniwaa.com/insight/3d-printers/total-metal-3d-printing-cost/ Accessed*: 2025-01-03.

[18] Dassault Systèmes. *Directed Energy Deposition, What is it and how does it work?,* available at: *https://www.3ds.com/make/guide/process/directed-energy-deposition Accessed*: 2025-01-03.

[19] Svetlizky, D. et al. (2021). *Directed energy deposition (DED) additive manufacturing: Physical characteristics, defects, challenges and applications*. Materials Today, Vol. 49 (October 2021), 271–295, Elsevier, ISSN 1369-7021, Kidlington, doi: 10.1016/J.MATTOD.2021.03.020.

[20] Imran, M. M., Che Idris, De Silva, A., L. C., Kim, Y. B., Abas, P. E. (2024). *Advancements in 3D Printing: Directed Energy Deposition Techniques, Defect Analysis, and Quality Monitoring*. Technologies, Vol. 12, No. 6 (June 2024), 86-157, MDPI, ISSN 2227-7080, Basel, doi: 10.3390/TECHNOLOGIES12060086.

[21] Dassault Systèmes. Powder Bed Fusion, How does it work?, available at: *https://www.3ds.com/make/guide/process/powder-bed-fusion Accessed*: 2025-01-03.

[22] Joshua, R. J. N. et al. (2024). *Powder Bed Fusion 3D Printing in Precision Manufacturing for Biomedical Applications: A Comprehensive Review*, Materials, Vol. 17, No. 3 (February 2024), Page 769, 769-799, MDPI, ISSN 1996-1944, Basel, doi: 10.3390/MA17030769.

[23] Franchitti, S. et al. (2018). *Investigation on Electron Beam Melting: Dimensional accuracy and process repeatability*, Vacuum, Vol. 157 (November 2018), 340–348, Elsevier, ISSN 1879-2715, doi: 10.1016/J.VACUUM.2018.09.007.

[24] Dassault Systèmes. Sheet Lamination, What is it and how does it work?, available at: *https://www.3ds.com/make/guide/process/sheet-lamination Accessed*: 2025-01-03.

[25] Loughborough University. *Sheet Lamination | Additive Manufacturing Research Group*, available at: *https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/sheetlamination/ Accessed*: 2025-01-03.

[26] Ngo, T. D., Kashani, A., Imbalzano G., Nguyen, K. T. Q., Hui, D.. (2018). *Additive manufacturing (3D printing): A review of materials, methods, applications and challenges*, Composites Part B: Engineering, Vol. 143 (June 2018), 172–196, Elsevier, ISSN 1879-1069, doi: 10.1016/J.COMPOSITESB.2018.02.012.

[27] EnvisionTEC. *SLCOM Selective Lamination Composites Object Manufacturing*, available at: *https://i3d.bg/wp-content/uploads/2020/07/2017-SLCOM1-1.pdf Accessed*: 2025-01-04.

[28] Taito 3D. *3D Printing in South Africa - Printing Services Johanesburg Blog*, available at: *https://www.taito3d.co.za/blogs/3d-printing.html Accessed*: 2025-01-06.

[29] Dassault Systèmes. *Photopolymerization, What is it and how does it work?*, available at: *https://www.3ds.com/make/guide/process/photopolymerization Accessed*: 2025-01-06.

[30] Dassault Systèmes. *Binder Jetting, What is it and how does it work?*, available at: *https://www.3ds.com/make/guide/process/binder-jetting Accessed*: 2025-01-06.

[31] TWI. *What is Binder Jetting?* available at: *https://www.twi-global.com/technical-knowledge/faqs/what-is-binder-jetting#HowdoesitWork Accessed*: 2025-01-07.

[32] Beyond Bynd. *3D Printing Technology: Material Jetting*, available at: *https://www.beyondbynd.com/3d-printing-technology-material-jetting-mj/ Accessed*: 2025-01-07.

[33] 3Dnatives. *What Are the Soluble Support Materials Available for 3D Printing?,* available at: *https://www.3dnatives.com/en/soluble-support-materials-available-for-3d-printing-020220244/ Accessed*: 2025-01-07.

[34] Xometry. *All About PVA 3D Printing Filament: Materials, Properties, Definition*, available at: *https://www.xometry.com/resources/3d-printing/pva-3d-printing-filament/ Accessed*: 2025-01-07

[35] Reifenhauser. *Biodegradable Products*, available at: *https://reifenhauser.com/en/circular-economy/biodegradable-products#Barrierefolie1337 Accessed*: 2025-01-07.

[36] Shah, H. H., Tregambi, C., Bareschino, P., Pepe, F. (2024). *Environmental and economic sustainability of additive manufacturing: A systematic literature review*, Sustainable Production and Consumption, Vol. 51 (November 2024), 628–643, Elsevier, ISSN 2352-5509, doi: 10.1016/j.spc.2024.10.012.

[37] Deskera (2025), *Plastics Manufacturing: Types of Plastic and Processes*, available at: *https://www.deskera.com/blog/plastics-manufacturing/ Accessed:* 2025-01-09.

[38] Hassan, M., Mohanty, A. K., Misra, M. (2024) *3D printing in upcycling plastic and biomass waste to sustainable polymer blends and composites: A review*, Materials & Design, Vol. 237 (January 2024), 25, Elsevier, ISSN 1873-4197, doi: 10.1016/j.matdes.2023.112558.

[39] Precious Plastic, *Precious Plastic Universe Explained*, available at: *https://www.preciousplastic.com/universe* Accessed: 2025-01-07

[40] Nikam, M., Pawar, P., Patil, A., Patil, A., Mokal, K., Jadhav, S. (2024). *Sustainable fabrication of 3D printing filament from recycled PET plastic*, Materials Today: Proceedings, Vol. 103 (2024), 115–125, Elsevier.

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