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Comparing additive manufacturing processes for distributed manufacturing

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Abstract: Additive manufacturing (AM) has been considered for distributed manufacturing. However, the consideration has usually concerned AM in general, not specific AM processes. This paper will look at the properties of different processes for distributed manufacturing from the perspective of the AM process and materials, post-processing, the requirements for devices and spaces, and raw materials. The findings show that powder bed fusion and binder jetting pose challenges for distributed manufacturing. The material extrusion process (MEX) can be affordable in a distributed form. It would be the ideal option when the demand for parts is low. VAT photopolymerization has similarities to MEX but is slightly more expensive and has a more demanding post-processing phase. However, it can be scaled up for higher production rates when demand is higher.

Keywords: 3D printing, distributed manufacturing, local manufacturing, additive manufacturing, rapid manufacturing, material extrusion, binder jetting, powder bed fusion, VAT photopolymerization

1. INTRODUCTION

Additive manufacturing (AM), more familiar as 3D printing, has shown potential and generated interest as a distributed manufacturing method (Verboeket *et al.,* 2021; Chekurov and Salmi, 2017). The logistics and scrap can be minimized by manufacturing closer to need and on an on-demand basis. For successful distributed manufacturing, the process should be capable of making end-use parts, and the materials and productivity should be considered in addition to space requirements and pre- and post-processing.

One interesting concept related to distributed manufacturing is digital spare parts (Chekurov *et al.,* 2021). Spares are made based on needs close to the end-user and on an on-demand basis. AM has been studied for distributed manufacturing from the perspective of different industries (Rauch *et al.,* 2018), using various use cases for spare parts (Durão *et al.,* 2017), and in terms of environmental and economic aspects (Huang et al., 2017). AM processes are often lumped together in these studies, and the different aspects of the processes are not taken into account. This study tries to fill this gap.

AM processes can be categorized in different ways. This article will follow ISO/ASTM terminology and classification (ISO/ASTM 52900, 2021). The AM processes studied are powder bed fusion (PBF), material extrusion (MEX), VAT photopolymerization (VP), material jetting (MJ), binder jetting (BJ), sheet lamination (SL), and directed energy deposition (DED). First, we explore which processes can produce end-use parts and consider productivity. These potential processes are then evaluated more specifically. The aim is to compare different AM processes for distributed manufacturing purposes.

The demands of distributed manufacturing differ from centralized manufacturing in that the AM machines should be more flexible so that more material can be made with the same device, post-processing should not require particular devices, the space requirements and infrastructure should not be demanding, and setup costs per production unit should be low, productivity high and lead time short. However, none of the AM processes fulfill all these criteria. The importance of these different aspects depends on the manufacturing case. Therefore, it is essential to study how the processes differ from each other in light of distributed manufacturing.

2. MATERIALS AND METHODS

2.1 Selection of potential processes for producing end-use parts

According to the scientific literature, the processes utilized to produce end-use parts are predominantly PBF and MEX (Table 1). The reason might be that PBF produces high-quality parts and MEX is the most widespread process. VP is also utilized in some cases, and BJ can be considered a growing technology with metal processes from HP and Desktop Metal. There are some studies on MJ, but the material properties do not meet the standards for mechanical end-use parts. SL is an uncommon process, and studies on it are hard to find. DED is primarily used in repairing wear and existing parts, and these applications are not included in this study.

The most common materials are plastics and metal alloys, but there are some studies with ceramics. Based on the findings, PFB, MEX, VP, and BJ were further studied from different perspectives in distributed manufacturing (Figure 1). The search terms included AM process names in aerospace, medical, consumer product, automotive, and energy sector applications. The purpose of the search was not to gather all the possible materials but to gain an overview and form an idea of which processes are easy to find and which are more challenging. The search results were utilized to select processes for more detailed analysis regarding aspects of distributed manufacturing.

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Table 1. Current AM processes and materials in end-use parts

	Materials
PBF	PA 2200, PA12, PA, Ti-6A-4V, 316L (Kestilä et al., 2018; Pirozzi et al., 2020; Huotilainen et al., 2019; Solaimani et al., 2021; Liu et al., 2019)
MEX	ABS, PLA, PEEK, PC, Ultem 9085, 316L (Liu et al., 2019; Nyman et al., 2021; Ait-Mansour et al., 2020; Najmon et al., 2019)
VP	Acrylates, Al2O3, PTMC (Guillaume et al., 2020; Zareanshahraki et al., 2021; Santoliquido et al., 2017)
MJ	ZrO2, RGD720, RGD875 (Koivuholma et al., 2021; Oh et al., 2019)
BJ	ZP 151, Infiltrated 316SS / Bronze (Rojas-Nastrucci et al., 2017; Mäkitie et al., 2010)
SL	Metal matrix composite, Paper (Hehr et al., 2019; Jahnke et al., 2018)
DED	316L, Ti6Al4V (Kang et al., 2021; Pirozzi et al., 2020)

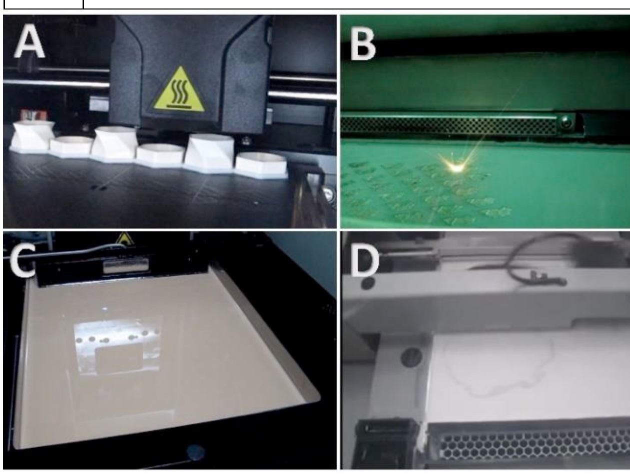

Figure 1. Studied AM processes: a) material extrusion, b) powder bed fusion, c) VAT photopolymerization and d) binder jetting

2.2 Data gathering on the processes

Data on the processes was gathered from the last ten years from Aalto University Digital Design Laboratory and generalized with different devices available in the market. The gathered data was based on the bookkeeping of the costs, device data sheets and instructions, utilization of the devices, and unstructured interviews with three (3) operators. This was then reflected on in light of the author's own experience and the operating and setting up of the machines. There have been multiple devices in the lab from each ISO/ASTM process class. We first looked at the raw materials that can be processed and the alternative materials that are easy to use with the same devices. The next step was to look at the post-processing requirements and devices for finalizing the end-use parts. The third was to consider the space that the AM devices and post-processing require. The fourth was to look at the cost level for setting up a single production unit. The fifth aspect was looking at how productive a single production unit can be and the relation of this to how many parts are in the build chamber. These are recognized as essential elements in previous studies (Verboeket *et al.,* 2021).

2.3 Synthesis of the data

After gathering the data, it was synthesized by comparing processes against each other one by one based on different aspects: material variability, post-processing facilities, space requirements, setup cost per production unit, and productivity and lead time. The variable and unitary production costs were left out since there are many studies about the costs of different AM processes, such as Salmi *et al.,* 2016. These also heavily depend on what kind of parts are made, which varies between processes. On the other hand, the cost per part can be offset by other benefits such as a shorter downtime, an electric warehouse, and simple logistics. Based on the comparison, the different aspects of the processes were rated on a scale of one to five.

3. RESULTS

3.1 Material variability and switching

In distributed manufacturing, it would be useful to be able to easily exchange one material for another. In processes based on powder (PBF, BJ), such an exchange takes time since different powder materials cannot be mixed. Often, only a designated machine is used for a single material in high-quality and certified industries. In MEX, the materials are filaments and can be easily switched. If the melting points of the materials are different and shift from a higher to a lower melting point, the residuals may block the nozzle. Some material needs to flow through the nozzle to remove residuals from the previous material. In VP, there are changeable vats for the material, which allow different materials. Also, the build platform needs to be material-specific. Changing the vat needs to be done carefully. Spilling the resin may dirty the device and lead to unsuccessful prints. Table 2 summarizes the raw materials and variability in different processes. In short, in MEX changing is easy, in VP it is doable, and in PBF and BJ it requires a significant amount of work and time and is usually not even recommended.

Table 2. Raw materials and material variability

	Raw materials
PBF	Powder – changing takes time or is not recommended Mostly metals and plastics, particle size requirements, material needs to be dry
MEX	Filament – easy to change Mostly plastics, filaments need to be dry and have a consistent diameter
VP	Resin in vat – can be changed, requires different vat Mostly plastics, photocurable with a specific wavelength, short lifespan
BJ	Powder – changing takes time or is not recommended Mostly metals, particle size requirements, material needs to be dry

3.2 Post-processing facilities

Since all the processes require some post-processing, this should be considered when looking at distributed manufacturing aspects. Table 3 shows the necessary post-processing facilities for different AM processes. Metal AM (PBF, BJ) almost always requires machining to achieve the required tolerance and surface quality and the removal of support structures. PBF for plastics only requires powder removal and bead blasting, unlike metals. In MEX, support structures can be manually removed or dissolved. VP only enables the manual removal of support structures, and parts also need to be washed and cured after printing. MEX is the easiest option, followed by VP. PBF and BJ require more post-processing facilities and substantial effort in metals. In addition, BJ parts need to be sintered, which requires time and specialized devices.

Table 3. Post-processing facilities for AM processes

	Post-processing facilities
PBF	Metal: machine shop, heat treatments Plastic: powder removal, bead blasting
MEX	Plastic: manual or dissolvable support removal
VP	Plastic: washing, UV curing, manual support removal
BJ	Metal: heat treatment / sintering, machine shop

3.3 Space requirements

Different AM devices require different kinds of space (Table 4). There are no considerable differences in the floor space requirements of the devices, the accessories, material handling, and post-processing have different requirements. MEX has little requirements for space: an office-type solution and a desk for support removal will suffice. Supports can also be dissolvable, in which case water and a sewer are needed. VP can be done in the office, but some resin will always spill on the floors and desks when taking parts out and in the post-processing stage. This makes places dirty, and also, washing the machines filled with flammable isopropanol requires good ventilation. PBF and BJ handle powders, and especially metal powder can be dangerous. There is often shielding gas in the device that needs to be ventilated. In addition, metal powders need to be stored in a fireproof cabinet or space. Since these also often require a machine shop for post-processing, only an industrial setting is acceptable.

Table 4. Space requirements for AM processes

	Space requirements
PBF	Industrial setting: ventilation, powder storage. Space for post-processing: machine shop
MEX	Office-type, water tap and sewer for soluble supports. Desk and tools for post-processing
VP	Separate office room, desk and tools for post-processing, post-processing is dirty
BJ	Industrial setting: ventilation, powder storage. Space for post-processing: machine shop

3.4 Setup costs per production unit

The costs related to AM are not simple. For example, part costs vary depending on the process, build orientation, and how complete the batch is. To make things more complicated, different processes behave differently (Salmi *et al.,* 2016). The following table looks at the cost to set up a manufacturing place – one hub for distributed manufacturing. The lower the cost, the easier it is to set up a wide distributed manufacturing network. Since MEX devices can be affordable and their space requirements easy to fulfill, their production unit setup costs are low. VP devices are slightly more expensive than MEX devices, but the space requirement is higher. However, the cost of setting up VP production units is still moderate, close to the low level. Setup costs for PBF can be remarkably high, as has been shown (Verboeket *et al.,* 2021). BJ has similar challenges as PBF in terms of the costs of setting up production units. Table 5 estimates the setup costs for a production unit on a scale of low, moderate, and high. These costs do not include operating costs.

Table 5. Cost estimation for setting up a production unit

	Setup costs: Machine, space, consumables, materials etc.
PBF	High: High machine price, need big powder material batch to operate
MEX	Low: Low machine price, cheap materials, a small material batch can be used
VP	Moderate: Affordable devices exist, materials are costly
BJ	High: High machine price, need big powder material batch to operate

3.5 Productivity and lead time

One crucial aspect is also the productivity of the device and the lead time (Table 6). From a productivity point of view, we looked at the average production rate and lead time for parts, how long it takes to manufacture them and make them ready for shipping.

Table 6. Productivity and lead time of different AM processes

	Productivity	Lead time
PBF	High: ideal for full builds	Slow Plastic build requires heating/cooling. Metals require post-processing
MEX	Low: ideal for single parts	Fast Requires only support removal
VP	Low: single parts Medium: full build	Medium Requires washing, curing and support removal
BJ	High: ideal for full builds	Slow Metals require post-processing

PBF and BJ are productive when the builds are complete, but lead times can be long since there is a need, for example, to cool down, sinter and post-process the parts. Many parts can be made in the same build, but getting the build and the parts ready takes time. The situation with MEX is similar: if there is one part on the entire build plate – the average time per part is almost the same. This makes MEX the preferred technique for producing single parts with a shorter lead time. VP has positive attributes from both perspectives. It can have medium productivity for complete builds and a faster response time for single parts. It would be a good compromise solution for distributed production that varies a lot – from more extensive series to one-of-a-kind parts that require fast delivery. For metals, keeping the lead times short is a challenge since post-processing requires machining.

4. DISCUSSION

AM processes can be used for end-use part manufacturing (Figure 2). In distributed manufacturing, many aspects need to be taken into account. Some AM processes are more straightforward to distribute than others, and some processes are not very suitable for manufacturing end-use parts. In order to make the right choice, the first thing is to match the material and the required quality. This may be fulfilled by some AM processes but not with all of them. After this, optimization related to locations and process selection can be done by taking into account multiple aspects. One challenge is that AM processes are not very well automated, but this is developing all the time.

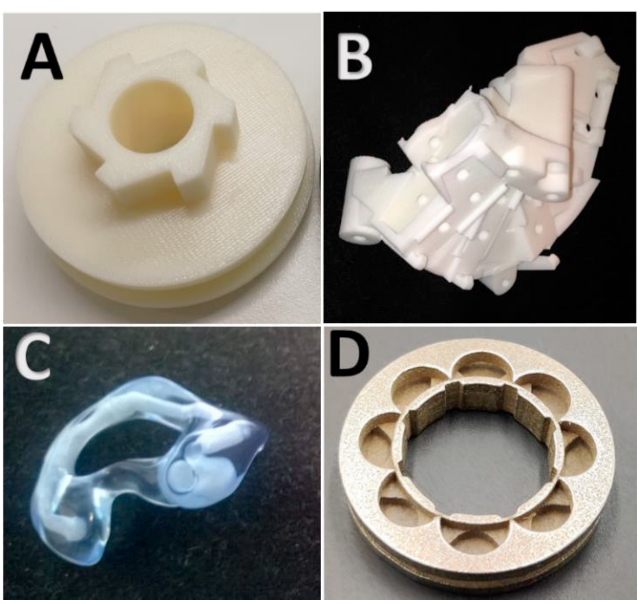

Figure 2. End-use parts made with AM processes: a) material extrusion, b) powder bed fusion, c) VAT photopolymerization, and d) binder jetting

If there is a need for personnel, the related costs should also be considered. Furthermore, since 3D printers mainly run independently, the person should manage multiple printers or have other tasks. Also, the more distributed the production network is, the more requirements there are for data processing. The de facto standard STL model for AM does not handle regular internal structures/lattices, manufacturing tolerances, geometric representation, curvature representation, or surface structures (Pei *et al.,* 2019). Another aspect is sending and handling the data safely (Alkaabi *et al.,* 2020).

MEX seems attractive and a potential process for distributed manufacturing. The material can be easily changed, and space and post-processing requirements are not demanding. Future development of MEX in metal and composites may open new possibilities for different industries. The distributed manufacturing option should also be investigated. One weakness is the visible layers of the parts and strength in the Z-direction. Also, MEX cannot be scaled up when producing many parts, unlike PBF, BJ, and VP, but this can be done by adding to the number of MEX printers. MEX would be a very good option when the demand for parts is low. VP has similarities with MEX. It is slightly more expensive and requires more post-processing and more space. One considerable aspect is that it seems scalable, suitable for single-part manufacturing and more extensive series. One problem might be that since the materials are photopolymers, they have limited material properties and parts tend to harden if they are exposed to light. VP offers excellent surface quality, but since the support structures are made from the same material as the parts, their removal requires manual work and affects the surface quality. This can be considered the weakest point of VP.

PBF fusion is the most utilized process in end-product manufacturing because of the quality and high productivity it delivers in full batches. However, it is not as flexible as the others, and its costs in distributed manufacturing can far outweigh the benefits (Verboeket *et al.,* 2021). PBF offers a well-scaled production time when the batches are complete, but making single parts once in a while is not practical. PBF produces consistent parts from plastics and metals. The most significant difference is that plastics do not require support structures while metals do. Plastics are more suitable for distributed manufacturing than metals due to the cost of devices, post-processing, metal powder handling, and space requirements.

Currently, BJ does not have a high potential for distributed manufacturing. However, there are numerous ongoing developments and risk funding invested in it. The aim is more to compete in the mass manufacturing of different components. However, this development may provide new openings for distributed manufacturing as well. The BJ process is essentially affordable and faster than PBF, which may lead to high productivity (Salmi *et al.,* 2016). In the future, BJ has potential between distributed and centralized manufacturing. BJ of plastics is mainly used for prototyping or visual models since the mechanical properties are insufficient. A recent development from HP and Desktop Metal has shifted BJ more toward metals even though it has existed there for dozens of years. Metal powder handling and post-processing are significant challenges in distributed manufacturing.

All the processes have their own characteristics related to distributed manufacturing. Figure 3 gives an overview of these. None of the processes are superior in all areas. Some processes are more flexible than others, and there are big differences in the setup costs of production units. Some require an industrial-type space rather than simply an office-type space, and post-processing makes a big difference. The limitation in this comparison is that the quality, pure part price, operation and personnel costs, and what actually will be additively manufactured have not been considered. For example, the metrology and tolerances of AM are not well explored (Akmal *et al.*, 2020; Vora and Sanyal 2020). Of course, when processes develop further, these characteristics will change. For example, the automation of the full 3D printing event and pre- and post-processing may turn the situation around. Currently, MEX can be considered to have the highest potential as a process for distributed manufacturing if the quality, materials, and other aspects are suitable. It is closely followed by VP, whereas PBF and BJ require more development, or the distribution cannot be as comprehensive as with MEX and VP.

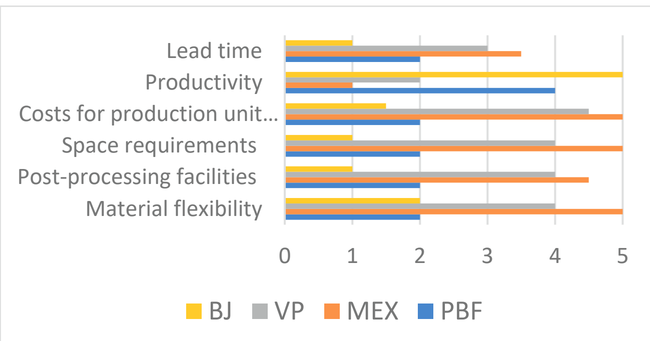

Figure 3. Comparison of the characteristics of different AM processes for distributed manufacturing (Scale 1–5)

AM is not the only manufacturing method considered and studied for distributed manufacturing. Various manufacturing processes, such as CNC machining, incremental sheet forming, and laser forming, do not require molds and have similar characteristic as AM (Lehtinen *et al.,* 2015; Casalino *et al.,* 2001; Wang *et al.,* 2004). These need to be taken into account when considering distributed manufacturing, and often especially metal AM processes require CNC machining in the post-processing stage.

5. CONCLUSIONS

This is one of the first attempts to investigate and compare the characteristics of different AM processes for distributed manufacturing. MEX is the most straightforward, flexible, and affordable process for distributed manufacturing. However, since BJ and PBF can deliver better quality and productivity, they may be chosen if the quality of MEX is not sufficient. VP seems to be positioned between MEX and the more demanding PBF and BJ. More studies are needed to explore which AM process is most suitable for different kinds of products and needs.

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