

1 ABSTRACT

In this report Selective Laser Sintering and Multi-Jet Fusion have been compared and contrasted with the feasibility of manufacturing a helicopter floor. It was found that the multijet fusion was a far better process for manufacturing the floor if the assumed volume in mind. Multi-jet was then compared to the current process of CNC milling. While the design of the helicopter floor was designed with the manufacturing capabilities in mind, if the floor was designed with additive manufacturing in mind then the multi-jet fusion could out perform any machining process.

2 TABLE OF CONTENTS

1	Abstract.....	1
3	Glossary of Acronyms	4
4	Introduction	5
5	Additive Manufacturing	6
5.1	Additive Manufacturing Technologies	6
6	Selective Laser Sintering	7
6.1	Machine capabilities	8
6.2	Materials & Properties.....	8
6.3	Manufacturing Feasibility	9
6.4	Environmental Impact.....	9
6.5	Health & Safety	10
6.6	Cost	10
7	Multi-Jet Fusion.....	11
7.1	Machining Capabilities.....	11
7.2	Material Properties	12
7.3	Manufacturing Feasibility	13
7.4	Environmental Impact.....	13
7.5	Health & Safety	14
8	Cost	14
9	Additive Manufacturing Comparison.....	15
10	CNC Milling.....	16
10.1	Machine Capabilities.....	16
10.2	Material Properties	16
10.3	Manufacturing Feasibility	16
10.4	Environmental Impact.....	17
10.5	Health & Safety	17
10.6	Cost	17
11	CNC vs MJF	18
12	Conclusion.....	19
13	References	20
14	Appendix	23
	Appendix A.....	23
	Appendix B.....	24

Appendix C.	25
Appendix D.....	26
Appendix E	27
Appendix F	28

3 GLOSSARY OF ACRONYMS

AM – Additive Manufacturing

SLS – Selective Laser Sintering

MJF – Multi-jet Fusion

PBF – Powder Bed Fusion

CNC – Computer Numerical Control

4 INTRODUCTION

The report will compare and contrast two different types of non-traditional and one traditional machining techniques with regards to manufacturing a helicopter flooring panel. Comparisons of machining capabilities, material properties, cost, manufacturing feasibility, environmental impact, and health and safety. A The two non-traditional techniques in question are Multi-jet Fusion (MJF) and Selective Laser Sintering (SLS) which are both a form of additive manufacturing (AM). Both techniques will be compared to CNC Milling and a conclusion will be drawn on the best process to manufacture a helicopter floor.

5 ADDITIVE MANUFACTURING

Additive manufacturing (AM), also known as 3D printing has been around commercially since the mid-1980's (Bourell, 2016). The AM that was first available was a stereolithographic (STL) machine which used ultraviolet (UV) to solidify a light-sensitive polymer (Wholers & Gornet, 2014). Since then there has been an exponential growth in AM. Firstly, the adoption of an AM into industry was through the form of rapid prototyping (Attaran, 2017). It reduced the lead time of bringing design to physical form greatly; General Motors have been using rapid prototyping for over twenty years (Fish, 2011), and now are on the verge of using AM components in the manufacturing process and add alternative-fuel vehicles to it range (Reuters, 2018). At this moment in time AM is now becoming an intricate part of the design and manufacturing process. While AM may not replace traditional manufacturing techniques but instead it will open the horizon of which products can be designed and produced (Thompson, et al., 2016). Currently the form of objects is driven by the designer's intent but limited by the manufacturing technology; with advancements in AM this is about to change.

5.1 ADDITIVE MANUFACTURING TECHNOLOGIES

There are many types of AM technologies that are available which can be seen in Appendix A. Currently powder bed fusion (PBF) was one of the first commercially adopted form of additive manufacturing on a large scale (Gibson, et al., 2014) . The four main types of PBF are Multi-jet fusion (MJF), Selective laser sintering (SLS), Direct metal laser sintering, and Electron beam melting (EBM) (3D Hubs, 2019). The SLS technology dates to 1992 where it was developed in the University of Texas at Austin (The University of Texas at Austin, 2012) and now is widely regarded as one of the most popular forms of AM. These techniques are different methods of fusing a material commonly in powder form into a solid form. Each technique varies in several ways and have different output qualities (Kruth, et al., 2005). All the process shares the same fundamental characteristics:

- A single or multiple thermal source this will induce the fusion of the powder particles
- Powder particle delivery system where an even layer of powder can be applied
- A control of the fusion of the powder to each layer
- Component build platform

(Gibson, et al., 2014)

6 SELECTIVE LASER SINTERING

Selective laser sintering (SLS) is the most commonly used industrial form of AM. This is due to several factors firstly, the availability of materials; EOS offer seventeen different alloys and fourteen plastics for their own SLS machines (EOS, 2019). Secondly, the dimensional accuracy that can be achieved by SLS is dependent on the laser width and layer thickness (Seepersad, et al., 2012). Typically, dimensional accuracy is $\pm 0.3\text{mm}$ with a minimum wall thickness of 0.7mm and minimum feature dimension of 0.3mm (Brandt, 2017). A SLS machine tends to have far better accuracy and resolution in X and Y axis rather than the Z axis, this is due to the Z axis being determined by the layer thickness (Gibson, et al., 2014).

A SLS printer consists of a powder feed system, build platform, CO_2 laser, galvanometers, and heaters. The build powder will be heated between the crystallisation temperature and melting point of the material throughout the build process. The laser will melt the powder required and keep the rest of the powder in thermal equilibrium until the part is complete then the bed will cool uniformly to stop any deformation and residual stress (Bourell, et al., 2017). A layer of powder will be spread across the build bed. The CO_2 laser will then fuse the cross-sectional design on the powder. Once the layer has been completed

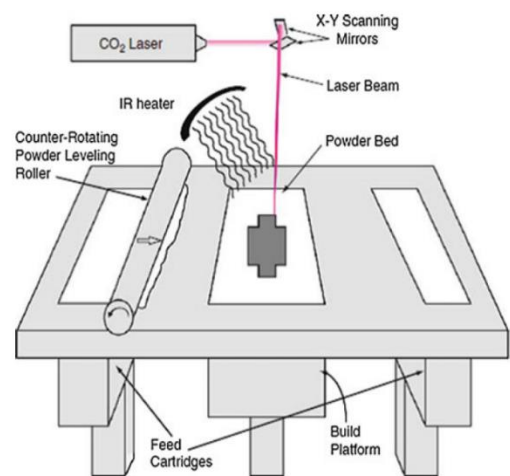


Figure 1 - Schematic of selective laser sintering

another layer will be spread onto the build bed and the process is repeated until completed. After the build process the part will need to be cooled this can take several hours.

While every SLS machine is different and all have a variation of different features, in this report the EOS systems will be considered due to them being considered industry leaders in AM systems.

6.1 MACHINE CAPABILITIES

- Accuracy: $\pm 0.3\text{mm}$
- Build Size: 750 x 550 x 550mm
- Layer Thickness: 100-120 microns
- Minimum Wall Thickness: 0.7mm
- Minimum Details 0.3mm

(EOS, 2019)

6.2 MATERIALS & PROPERTIES

SLS have a variety of different materials that can be used, EOS offer a range of twenty plastics and thirteen metals. This cover a wide range of different properties from polyamide 12 with reinforced carbon-fibre with excellent strength to weight ratio, to PEBA 2301 which has high elasticity and strength (EOS, 2019) Appendix B.

The material which will be used to compare the SLS technology will be CarbonMide. It has extreme strength and stiffness and has a very high strength to density ratio. This would make an ideal material for replacing metal floor panel in a helicopter.

The properties of CarbonMide is different in all axis, this is due to the layering of the SLS printer. Appendix B gives the details of such tensile modulus and tensile strength, this means with careful design the floor could have a tensile strength of 72 MPa (EOS, 2019). Carbonmide has a density of 1040 kg/m^3 the strength to density ration is 69,230:1.

The surface finish from SLS machine if not a touch critical part is acceptable, but if a smooth finish is required then post processing is needed

6.3 MANUFACTURING FEASIBILITY

When considering the feasibility of mass manufacturing a product using SLS, the volume of the product must be determined before manufacturing technologies are explored. To determine the volume Airbus the largest helicopter manufacturer can be used as the example, in 2018 Airbus sold 356 helicopters (Airbus, 2018). Therefore, if a floor for each of those helicopters need to be produced then it can be assumed that the volume needed is low. Therefore, based on that assumption SLS manufacturing solution can be considered.

SLS has several factors that should be considered in the design and manufacturing phases to achieve maximum output and quality. The main factor is the build size; this can limit the size of the product or how many products can be printed at once. If the product is small, then multiple parts can be stacked to better utilise the build capacity (Thompson, et al., 2016). The different properties at different axis will also be a contributing factor to the stacking process.

Print time is a factor to be considered, while the time of the printing process could be low, an equal time is needed for the cooling process and for post processing. Due to the powder bed being heated just below melting point the time of the cooling process is substantial.

The SLS bed is more than capable to print the helicopter floor as a single piece. While this would make the process far easier, to better utilise the bed capacity the floor should be broken down into pieces to fill the bed capacity. This will reduce the waste of material thus reducing cost.

6.4 ENVIRONMENTAL IMPACT

The environmental impact of SLS is very similar to other PBF processes. The excess powder which is not used in the build process usually needs be disposed of. While some plastics are recyclable others are not so, which means will have a big effect on the environment (Faludi, et al., 2015).

One big effect that the SLS process has on the environment is the fumes and dust what is given off throughout the process, these must be extracted and correctly filtered. High levels of particles can be hazardous to humans as well as the environment (Bours, et al., 2017).

6.5 HEALTH & SAFETY

The health and safety aspect of SLS is very important, as expected when a powder is sintered it releases toxic smoke, fumes and dust into the air which are hazardous. These fumes will need to be extracted and filtered before they are let into the atmosphere. (Jinghai, et al., 2016)

With SLS and other PBF process the dust by-product from the process is highly combustible and should be carefully extracted and disposed. Extraction would also be needed in the post processing where large amount of dust and particles will be released with machining (HSE, 2019).

6.6 COST

A SLS machine has a very high start-up cost, in industrial SLS manufacturing machine such as the EOS P 500 would cost in excess of 350,000 GBP (EOS, 2019). With the need for infrastructure as well the price will rise considerably. To make this process cost effective the SLS machine will need to be printing continuously to gain a return on investment. Based upon the assumptions that were made earlier regarding volume then to just print the helicopter floor would not be a cost-effective method.

To make this method viable many other parts need to be printed so allow the printer to work continuously. Instead of build stacking just helicopter flooring, several parts could be printed in the same build which would all be used on the same helicopter. These parts could be from exterior parts to cockpit parts however all possess the same properties as the floor, which may not be required but none the less would make the build more efficient.

A further cost of SLS is the waste powder that remains after the build. Once the powder has reached its maximum use time of sixty hours, then it will have to be disposed of otherwise it will lose its integrity and will not perform as expected (RP Platform, 2017). This is a seen to be PBF biggest downfall, while AM only uses the required material there is still a large amount of waste if not managed correctly.

A Case study carried out by 3D hubs which had quotes from six different 3D print services in the US, for one-off part and a batch of 30. They compared SLS against MJF the case study can be seen in

Appendix D. The average parts cost of one part was 46.45 USD and per unit of thirty was 25.85 USD.

While both the prices were very competitive the lead time for such parts was seven days.

7 MULTI-JET FUSION

The HP Multi-Jet Fusion (MJF) is another PBF process, in many respects it is very similar to SLS printing but instead of the use of a laser as the heat source, the MJF uses a fusing agent which promotes the absorption of infra-red light (HP, 2019). Very similar to a paper printer, the MJF printer scans across the bed of powder and deposits the fusing agent where required. Once that process is complete the infra-red lights passes over the bed setting the layer, this will be repeated until the parts are complete. The dimensional accuracy is $\pm 0.2\text{mm}$, a layer thickness of 0.6mm and a minimum detail of 0.25mm . The MJF has a layer thickness of 70-100 microns which allows for more details and increased strength due to better fusion of the layers (Goodridge & Ziegelmeier, 2017).

Just as SLS the powder is heated just below melting point until the build is complete, the difference between MJF and SLS is that the powder in the MJF is forced cooled thus decreasing the build time and gives far better control over the final properties of the material. Due to the decreased cooling time, HP claim that the MJF is 10 times faster than selective SLS and FDM machines (HP, 2019) printing the same parts.

7.1 MACHINING CAPABILITIES

- Accuracy: $\pm 0.2\text{mm}$
- Build Size: $380 \times 285 \times 380\text{mm}$
- Layer Thickness: 70-100 microns
- Minimum Wall Thickness: 0.6mm
- Minimum Details 0.25mm

(HP, 2019)

7.2 MATERIAL PROPERTIES

The biggest constraint of MJF is the very limited amount of materials that are currently available, currently HP offer three plastics which are PA12, PA12 GB and PA11. While more materials are planned, currently it is very limited (HP, 2019).

The material which will be used to compare the MJF printer is PA12 plastic, it is strong, has good chemical resistance and has good elongation at break. In Appendix C, the PA12 datasheet boasts tensile strength of 48MPa in any axial direction (HP, 2019), while it may not be the strongest material the technology of MJF allows it to have it in all directions. This allows the part to be stacked in the printed in the most efficient way (Sillani, et al., 2019). MJF also allows for different material properties in the same part, this is achieved by changing the concentration or the fusing agent in each voxel of the part. Properties that could be controlled are:

- Dimensional accuracy and detail
- Surface roughness, texture, and friction coefficient
- Tensile Strength, elasticity, hardness, and other material properties
- Electrical and thermal conductivity
- Opacity or translucency in plastics
- Colour: embedded and at the surface

(HP, 2019)

While HP claim to have consistent surface finish of all parts at all positions in the XY plane of the MJF. However, research carried out suggested that the surfaces of parts closest to the centre of the bed have a far rougher surface finish when compared to other positions on the bed (Sillani, et al, 2019). This would be a great quality concern with the integrity of the material possibly being compromised. If the surface finish of the product has high importance post processing can be carried out. The post processing will give better surface finish and can be from traditional machining techniques such as

milling, turbing and grinding. One consideration that should be taken into account is that MJF parts have a dark grey colour due to it absorbing IR light better (HP, 2019).

7.3 MANUFACTURING FEASIBILITY

As previously stated the volume of the helicopter floor can be assumed to be 356 units per year. Taking that into consideration the MJF would be an ideal process for the manufacturing of the part. The biggest constraint that hinders MJF is the bed size with dimensions of 380 x 285 x 380mm (HP, 2019). Due to there being such a small bed size parts such as the helicopter floor need be redesigned to accommodate the build size. This could work in the favour regarding the strength and dimensional accuracy. A flaw of all PBF is warping of flat parts over large dimensions (Beitz, et al, 2019) the MJF counter this flaw by having the force cooling system, by reducing the cooling time by 50% and printing long dimension parallel to the XY plane (HP, 2019).

HP claim that the MJF can print a full bed of parts 10 times faster than an equivalent SLS machine this can be seen in Appendix E. This can also be confirmed with the 3D hubs case study which states that MJF had a lead time of 4 days compared to SLS 7 days (3Dhubs, 2019).

7.4 ENVIRONMENTAL IMPACT

HP tried to make the MJF as environmentally friendly by refining the process (HP, 2019). The excess powder is 80% reusable at the post processing station, where the powder is cleaned and filtered back into the filling station. At the post process station all the dust from the cleaning process is also filtered and fed back into the filling station. However, HP currently only offer PA12 and PA11, while both are reusable in the process, they have a big effect on the environment due to PA12 being derived from mainly petroleum sources (Carraher, 2017). PA11 while still needs natural resourced to be made, the resources are bio-based and renewable (Filippone, et al., 2010).

7.5 HEALTH & SAFETY

The MJF greatly reduces the risk to health and safety compared to other PBF machines. Due to the IR light generating far less energy than SLS and other such PBF technologies. The extraction of the post processing is still necessary to ensure that all the fumes and dust is correctly disposed of. MJF allows for the collected powder and dust to be recycled back into the process to be used again (Jinghai, et al., 2016).

8 COST

As most PBF the start-up cost is very high a typical HP MJF cost 350,000 GBP (HP, 2019), but where other PBF machines need infrastructure such as extraction a MJF only needs an industrial power source, this is due to the filtration and extraction being built into the machine. This will greatly reduce the cost and space required.

To make the MJF a cost-effective process the bed would need to be filled as much as possible, however unlike some PBF the build capacity does not need to be completely full to build parts, if single or very small volume of small parts are required the bed can be filled to the required dimensions (HP, 2019). Having the ability to change the properties of each part in the build bed is a massive advantage compared to other PBF processes. This would give the MJF far superior versatility compared to other PBF processes.

HP claim the ability to recycle up to 80% of the powder that is not used in the build of parts, which can then be fed back into the fill station for future prints (HP, 2019). This would substantially reduce the running cost of the process and reduce the cost of disposal of the powder.

The case study that 3D hubs conducted showed that the MJF came in cheaper at 46.28 USD to the SLS process 46.45 USD for one-off part but when it came to the 30-part build MJF 28.75 USD compared to 25.85 USD (3Dhubs, 2019). HP claim that the MJF is 50% cheaper compared to a similar value SLS machine printing 1.4 full build chambers (Appendix E). But as seen in a real-world case this

may not be true. While we no definitive true price due to the mark-up that the companies will be making on the product. Also, to be considered is that the companies may want to wait to fill the build capacity in the SLS machine to ensure its cost-effectiveness, while the MJF can reduce build capacity thus reducing cost and time.

Where the MJF excelled was the lead time, while there is no quantitative value of the price of fast production it is clear that while the price is slightly higher, it is almost 50% quicker thus produce more double the parts in half the time. HP claim that in a 38-hour print time of gears a SLS machine will print 1000 gears compared to the MJF printing 12,600 (HP, 2019).

9 ADDITIVE MANUFACTURING COMPARISON

To compare the two different AM process, quantitative values of each comparative of MJF and SLS is given. In Table 1 Process Comparison Matrix the determinates rating will be multiplied by the importance to give each process a score.

Key: Green 50+, Orange 30 – 49 and Red 0-29

Determinate	Importance	MJF rating	MJF	SLS rating	SLS
Machining Capabilities	7	8	56	6	42
Material Properties	10	6	60	8	80
Feasibility	8	6	48	7	56
Environmental Impact	4	7	28	4	16
Health & Safety	6	7	42	6	36
Cost	10	5	50	4	40
Total			284		270

Table 1 Process Comparison Matrix

MJF outsourced SLS in 4 out of 6 determinates based upon the outcome the MJF will be the AM process that will be compared to CNC milling to make the helicopter floor.

10 CNC MILLING

CNC milling is classed as traditional method of machining. It is one of the most common methods of machining, and it used in a variety of industry's such as automotive, aerospace and electrical. Due to CNC milling machines being around since the 1970's (Boble, 1986) there is wide variety of machines available. The rule of thumb is the larger the size and more accurate the machine is the more it costs.

10.1 MACHINE CAPABILITIES

- Accuracy: $\pm 0.10\text{mm}$
- Minimum Feature: $\varnothing 0.5\text{mm}$
- Layer Thickness: 70-100 microns
- Hole: $\varnothing 0.5\text{mm}$
- Internal Edges: R 0.25mm

10.2 MATERIAL PROPERTIES

CNC machining offer a wide range of materials that can be machined such as: Aluminium, Steel, Brass and Copper (Overby, 2010), as well as a range of plastics. In this comparison the helicopter floor was currently made from Aluminium, taking that into consideration the assumption that the floor is 6061-T6 which is a common used Aluminium in aerospace (Sanders, 2001).

Aluminium 6061 is a high strength, heat treatable alloy. It has good corrosion resistance and can be welded; however welding points will have lower strength (Aalco, 2019). The 6061 is T6 tempered so gain better hardness and age the material; this makes 6061 ideal for the machining process. The alloy will be machined at a lower hardness, which will reduce the strain on in the machining process. Tooling life will be increased, and less coolant can be used. (Li, et al., 2017)

10.3 MANUFACTURING FEASIBILITY

As assumed earlier the volume is 356 units per year. To get the maximum efficiency out of a CNC machine high volume is required, this is due to the amount of set up time that is required and the change of tooling (Smid, 2010). 356 units is far to low to make the CNC milling a cost-effective option if the CNC machines sole operation is the helicopter floor. While other operations could be used as

well as the helicopter floor to justify the cost of a CNC, however the time to set up would be rather high and would have a lot of down time.

A CNC milling machine as well as all subtractive process are unable to make hollow/voids or complicated internal geometry in a single part. With the tool being powered by a spindle there are some accessibility complications with some geometries. This can be overcome by manufacturing smaller components and assembling them, but this does come at increased cost.

10.4 ENVIRONMENTAL IMPACT

The CNC machine has many consumables that if not disposed of correctly would have a massive effect on the environment. The consumables that would need to be disposed of are: Coolant, hydraulic fluid, air and oil filters and, oil. While some of these consumables can be recycled, most will be disposed of due to the cost of the recycling (Faludi, et al., 2015).

10.5 HEALTH & SAFETY

A CNC machine has relatively low health and safety risk; due to the machine operating in an enclosed manor. When the machine is in operations the entry door will be an interlock, so no access is possible (AXYZ, 2019). The greatest safety concern would be the correct disposal of excess material and coolant (HSE, 2019).

10.6 COST

The cost of a CNC machine is very high, the cost is partial the machine as well as the infrastructure needed. Extraction, coolant services and material disposal are necessary for constant operations. A Typical CNC milling machine will cost in excess of 200,000 USD (XYZ, 2019). While the day to day energy consumption is said to be low according to (Li, et al., 2017). Other consumables such as coolant, hydraulic fluid, air and material come at a cost. While the coolant can be filtered and recycled the other necessary services are not. The material waste from the subtractive nature of this process is a cost that can not be avoided, while the material can be recycled the company will not recover the cost of the waste.

The maintenance cost of a CNC machine is very high; elements such as tooling, magazines wear and backlash are just some of the maintenance that is required often. While these elements can be costed into a maintenance plan, and preventive measure can be put in place to extend the life of parts and tooling (XYZ, 2019).

11 CNC vs MJF

To compare CNC milling vs MJF the same determinates were used, and quantitative values given to the rating of each multiplied by the importance.

Key: Green 50+, Orange 30 – 49 and Red 0-29

Determinates	Importance	MJF Rating	MJF Score	CNC Rating	CNC Score
Machining Capabilities	7	8	56	5	35
Material Properties	10	6	60	7	70
Feasibility	8	6	48	5	40
Environmental Impact	4	7	28	7	28
Health & Safety	6	7	42	9	54
Cost	10	5	50	5	50
Total			284		277

Table 2 Process Comparison Matrix of MJF vs CNC

MJF out scored CNC by 7 points overall.

Each process has its advantages and disadvantages, and both would be adequate to manufacture the floor if criteria is met. If volume of the floor was hundreds of thousands of units then the CNC would be a better option. But at the current volume assumed the MJF is a far better option.

If the helicopter floor was manufactured using MJF the cost savings would be substantial compared to a CNC milled billet. The helicopter floor when made from Aluminium had a mass of 13.9kg but when made from PA66 it has a mass of 5.7kg this can be seen in Appendix F. That is a weight saving of 8.2kg which would save substantial amount of fuel.

12 CONCLUSION

While each process compared would be adequate to manufacture the helicopter floor, they would not be working at their full potential and not working to their strengths. The CNC machine would be an ideal solution if the volume was in the hundreds of thousands. While the MJF is the process chosen at the current volume, due to its versatility in part production and material properties, it also would be lowest cost overall.

While MJF would be able to print the floor with ease however, to get the MJF working to its full potential the design of the floor needs to be designed with AM in mind. Features that were never capable with subtractive manufacturing are now possible. Complex internal lattice structures are a common element in today's AM; in the past this would never be possible. With the use of CAD and topology simulation parts can be designed with the minimum amount of material, this cuts down machining time, material cost and saves weight.

If other parts of the helicopter would be manufactured by MJF it would greatly save cost of purchasing the parts from external sources, it would increase the efficiency of the MJF and give the ability to rapid prototype new parts.

AM is not just a new way of manufacturing but it's a new ideology of design and manufacturing. The capabilities are endless but are held back by the traditional traits and methods of design. The designers of tomorrow will get the full potential out of AM.

13 REFERENCES

- 3D Hubs, 2019. *www.3dhubs.com*. [Online]
Available at: <https://www.3dhubs.com/knowledge-base/additive-manufacturing-technologies-overview>
[Accessed 20 March 2019].
- 3Dhubs, 2019. *www.3dhubs.com*. [Online]
Available at: <https://www.3dhubs.com/knowledge-base/hp-mjf-vs-sls-3d-printing-technology-comparison#cost>
[Accessed 5th April 2019].
- Aalco, 2019. *www.aalco.co.uk*. [Online]
Available at: http://www.aalco.co.uk/datasheets/Aluminium-Alloy-6061-T6-Extrusions_145.ashx
[Accessed 10 April 2019].
- Airbus, 2018. *www.airbus-group.com*. [Online]
Available at: <https://web.archive.org/web/20140102190746/http://www.airbus-group.com/airbusgroup/int/en/our-company/What-we-do/airbus-helicopters.html>
[Accessed 30 March 2019].
- Attaran, M., 2017. The Advantages of Additive Manufacturing over Traditional Manufacturing. *The Rise of 3-D Printing*, 2(1), pp. 677-688.
- AXYZ, 2019. *www.axyz.com*. [Online]
Available at: https://www.axyz.com/us/wp-content/uploads/sites/2/2016/11/en-en_axyzcncroutermanual.pdf
[Accessed 12 April 2019].
- Beitz, S. et al., 2019. Influence of Powder Deposition on Powder Bed and Specimen Properties. *Materials*, 12(2), p. 297.
- Boble, D., 1986. *Forces of Production: A Social History of Industrial Automation*. 5 ed. New Jersey: Transaction Publisjers.
- Bourell, D. et al., 2017. Materials for additive manufacturing. *CIRP Annals*, 66(2), pp. 659-681.
- Bourell, D. L., 2016. Perspective on Additive Manufacturing. *Annual Review of Materials Reseach*, 46(1), pp. 1-18.
- Bours, J. et al., 2017. Addressing Hazardous Implications of Additive Manufacturing: Complementing Life Cycle Assessment with a Framework for Evaluating Direct Human Health and Environmental Impacts.. *Journal of Industrial Ecology*, 21(12), pp. S25-S36.
- Brandt, M., 2017. *Laser Additive Manufacturing: Materials, Design, Technologies, and Applications*. 1 ed. London: Woodhead Publishing Ltd.
- Carraher, C., 2017. *Introduction to Polymer Chemistry*. 1 ed. London: CRC Press.

William May-White
P101973

EOS, 2019. *www.eos.com*. [Online]
Available at: <https://eos.materialdatacenter.com/eo/>
[Accessed 29 March 2019].

EOS, 2019. *www.eos.info*. [Online]
Available at: <https://www.eos.info/material>
[Accessed 22 March 2019].

Faludi, J., Bayley, C., Bhogal, S. & Iribarne, M., 2015. Comparing environmental impacts of additive manufacturing vs traditional machining via life-cycle assessment. *Rapid Prototyping Journal*, 21(1), pp. 14-33.

Filippone, G., Dintcheva, N., La Mantia, F. & Acierno, D., 2010. Filippone, G., Dintcheva, N.T., La Mantia, F.P. and Acierno, D., 2010. Selective localization of organoclay and effects on the morphology and mechanical properties of LDPE/PA11 blends with distributed and co-continuous morphology. *Journal of Polymer Science Part B: Polymer Physics*, 48(5), pp. 600-609.

Fish, E., 2011. Rapid prototyping how its done at GM: Additive manufacturing technology is helping the automaker reduce product development times and costs. *Automotive Design & Production*, 123(5), pp. 46-48.

Gibson, I., Rosen, D. & Stucker, B., 2014. *Additive manufacturing technologies*. 17 ed. New York: Springer.

Goodridge, R. & Ziegelmeier, S., 2017. Powder bed fusion of polymers.. *Laser Additive Manufacturing*, 1(1), pp. 181-204.

HP, 2019. *www.hp.com*. [Online]
Available at: h20195.www2.hp.com/v2/GetDocument.aspx?4AA7-1532ENA
[Accessed 2 April 2019].

HP, 2019. *www.hp.com*. [Online]
Available at: <https://www8.hp.com/us/en/printers/3d-printers.html>
[Accessed 6 April 2019].

HP, 2019. *www.hp.com*. [Online]
Available at: <http://h20195.www2.hp.com/v2/GetPDF.aspx/4aa6-8157eew.pdf>
[Accessed 7 April 2019].

HP, 2019. *www.hp.com*. [Online]
Available at: <http://www8.hp.com/h20195/v2/GetPDF.aspx/c06195607.pdf>
[Accessed 7 April 2019].

HP, 2019. *www.hp.com*. [Online]
Available at: <http://h20195.www2.hp.com/v2/GetDocument.aspx?docname=4AA7-1532ENA>
[Accessed 7 April 2019].

HSE, 2019. *www.hse.gov.uk*. [Online]
Available at: <http://www.hse.gov.uk/research/rrpdf/rr1146.pdf>
[Accessed 6th April 2019].

HSE, 2019. *www.HSE.gov.uk*. [Online]
Available at: <http://www.hse.gov.uk/research/rrpdf/rr974.pdf>
[Accessed 11 April 2019].

William May-White
P101973

Jinghai, Y. et al., 2016. Emission of particulate matter from a desktop three-dimensional (3D) printer. *Journal of Toxicology and Environmental Health*, 79(11), pp. 453-465.

Kruth, J., Mercelis, P. & Van Vaerenbergh, J., 2005. Binding mechanisms in selective laser. *Rapid Prototype*, 11(1), pp. 26-36.

Li, L., Li, C., Tang, Y. & Yi, Q., 2017. Influence factors and operational strategies for energy efficiency improvement of CNC machining. *Journal of Cleaner PProduction*, 161(7), pp. 220-238.

Overby, A., 2010. *CNC Machining Handbook: Building, Programming, and Implementation*. 1 ed. New York: McGraw-Hill Inc.

Reuters, 2018. *www.reuters.com*. [Online]
Available at: <https://www.reuters.com/article/us-general-motors-parts/gm-bets-on-3d-printers-for-cheaper-and-lighter-car-parts-idUSKBN1I408K>
[Accessed 18 March 2019].

RP Platform, 2017. *www.amfg.ai*. [Online]
Available at: <https://amfg.ai/wp-content/uploads/2017/12/The-Evolving-SLS-Production-Cycle.pdf>
[Accessed 10 April 2019].

Sanders, R., 2001. Technology Innovation in aluminium Products. *The Journal of The Minerals*, 53(2), pp. 212-25.

Seepersad, C. et al., 2012. A designer's guide for dimensioning and tolerancing SLS parts. *In Solid Freeform Fabrication Symposium*, 14(1), pp. 921-931.

Sillani, F., Kleijnen, R., Vetterli, R. & Wegener, K., 2019. Selective laser sintering and multi jet fusion: Process-induced modification of the raw materials and analyses of parts performance. *Additive Manufacturing*, 27(1), pp. 32-41.

Smid, P., 2010. *CNC control setup for milling and turning : mastering CNC control systems*. 1 ed. New York: New York: Idustrial Press.

The University of Texas at Austin, 2012. *www.utexas.edu*. [Online]
Available at: <http://www.me.utexas.edu/news/news/selective-laser-sintering-birth-of-an-industry>
[Accessed 20 March 2019].

Thompson, M. et al., 2016. Design for Additive Manufacturing: Trends, opportunités, considerations, and constraints. *CIRP Annals - Manufacturing Technology*, 65(2), pp. 737-760.

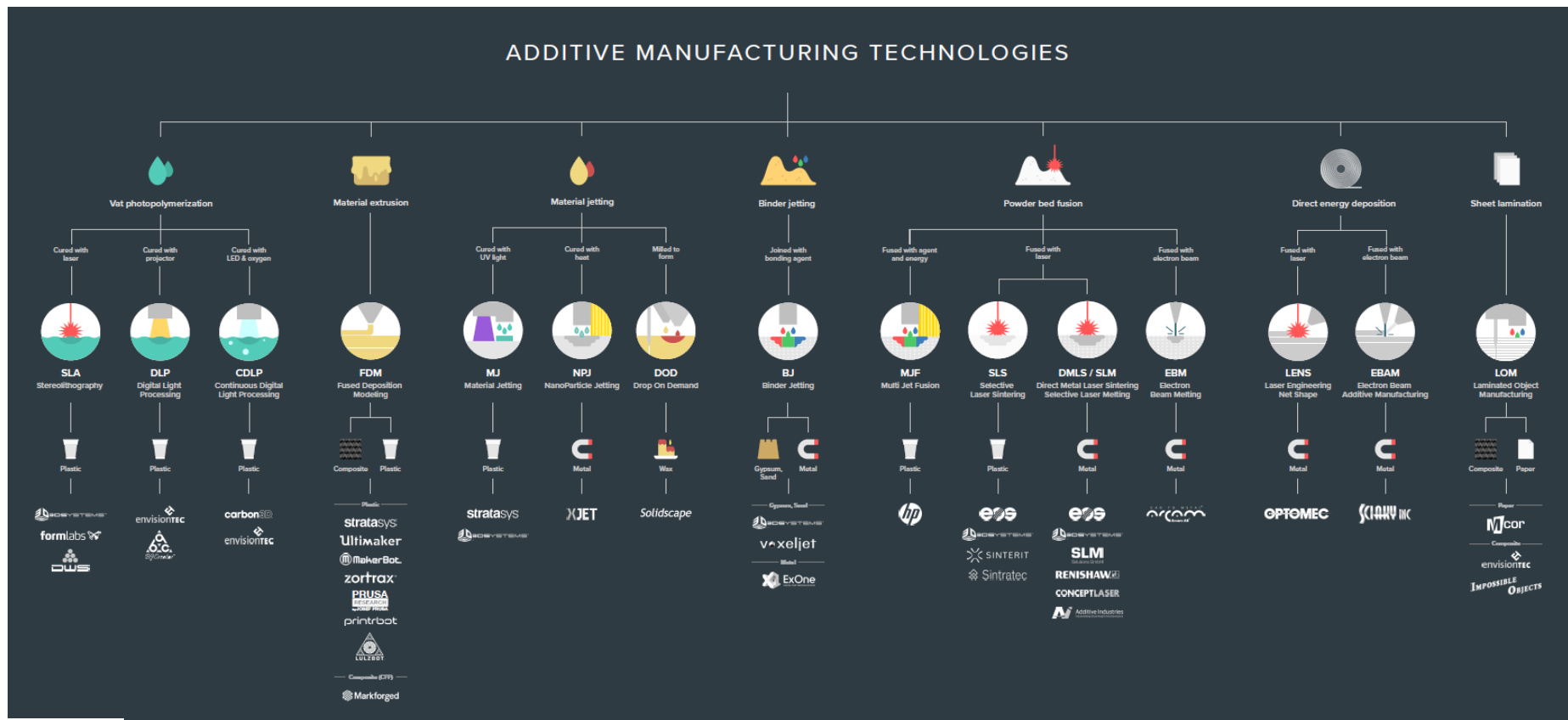
Wholers, T. & Gornet, T., 2014. History of Additive Manufacturing. *Wohlers Report*, 24(1), p. 118.

XYZ, 2019. *www.xyz.com*. [Online]
Available at: <https://www.xyzmachinetools.com/machine-tools/vertical-machining-centres/umc-5x/>
[Accessed 11 April 2019].

14 APPENDIX

APPENDIX A.

Additive manufacturing technology map diagram



Appendix A

APPENDIX B.

CarbonMide Data Sheet

GENERAL			
Properties			
3D Data			
Therm			
Other			
CarbonMide PA12-CF			
The properties of parts manufactured using additive manufacturing technology (e.g. laser sintering, stereolithography, Fused Deposition Modelling, 3D printing) are, due to their layer-by-layer production, to some extent direction dependent. This has to be considered when designing the part and defining the build orientation.			
3D Data	Value	Unit	Test Standard
Tensile Modulus			ISO 527
X Direction	6100	MPa	
Y Direction	3400	MPa	
Z Direction	2200	MPa	
Tensile Strength			ISO 527
X Direction	72	MPa	
Y Direction	56	MPa	
Z Direction	25	MPa	
Strain at break			ISO 527
X Direction	4.1	%	
Y Direction	6.3	%	
Z Direction	1.3	%	
Charpy impact strength			ISO 179/1eU
+23°C, X Direction	20.5	kJ/m ²	
+23°C, Y Direction	27.5	kJ/m ²	
+23°C, Z Direction	5.5	kJ/m ²	
Charpy notched impact strength			ISO 179/1eA
+23°C, X Direction	5.3	kJ/m ²	
+23°C, Y Direction	4.4	kJ/m ²	
+23°C, Z Direction	2.1	kJ/m ²	
Volume resistivity			
X Direction	0.0463	Ohm*m	IEC 62631-3-1
Y Direction	0.107	Ohm*m	IEC 60093
Z Direction	3.08	Ohm*m	IEC 60093

GENERAL			
Properties			
3D Data			
Therm			
Other			
CarbonMide PA12-CF			
Other properties	Value	Unit	Test Standard
Density (lasersintered)	1040	kg/m ³	EOS Method

APPENDIX C.

HP PA 12 Data Sheet

Technical specifications⁸

Category	Measurement	Value	Method
General properties	Powder melting point (DSC)	187° C/369° F	ASTM D3418
	Particle size	60 µm	ASTM D3451
	Bulk density of powder	0.425 g/cm ³ /0.015 lb/in ³	ASTM D1895
Mechanical properties	Density of parts	1.01 g/cm ³ /0.036 lb/in ³	ASTM D792
	Tensile strength, max load ⁹ XY, XZ, YX, YZ	48 MPa/6960 psi	ASTM D638
	Tensile strength, max load ⁹ ZX, ZY	48 MPa/6960 psi	ASTM D638
	Tensile modulus ⁹ XY, XZ, YX, YZ	1800 MPa/261 ksi	ASTM D638
	Tensile modulus ⁹ ZX, ZY	1800 MPa/261 ksi	ASTM D638
	Elongation at break ⁹ XY, XZ, YX, YZ	20%	ASTM D638
	Elongation at break ⁹ ZX, ZY	15%	ASTM D638
	Flexural strength @ 5% ¹⁰ XY, XZ, YX, YZ	70 MPa/10150 psi	ASTM D790
	Flexural strength @ 5% ¹⁰ ZX, ZY	70 MPa/10150 psi	ASTM D790
	Flexural modulus ¹⁰ XY, XZ, YX, YZ	1800 MPa/261 ksi	ASTM D790
	Flexural modulus ¹⁰ ZX, ZY	1800 MPa/261 ksi	ASTM D790
	Impact notched @ 3.2 mm, 23° C, XY, XZ, YX, YZ	3.6 kJ/m ²	ASTM D256 Test Method A
	Impact notched @ 3.2 mm, 23° C, ZX, ZY	3.5 kJ/m ²	ASTM D256 Test Method A
	Shore Hardness D, XY, XZ, YX, YZ, ZX, ZY	80	ASTM D2240
Thermal properties	Heat deflection temperature @ 0.45 MPa, 66 psi, XY, XZ, YX, YZ	175° C/347° F	ASTM D648 Test Method A
	Heat deflection temperature @ 0.45 MPa, 66 psi, ZX, ZY	175° C/347° F	ASTM D648 Test Method A
	Heat deflection temperature @ 1.82 MPa, 264 psi, XY, XZ, YX, YZ	95° C/203° F	ASTM D648 Test Method A
	Heat deflection temperature @ 1.82 MPa, 264 psi, ZX, ZY	95° C/203° F	ASTM D648 Test Method A
Reusability	Minimum refresh ratio for stable performance	20%	
Recommended environmental conditions	Recommended relative humidity	50–70% RH	
Certifications	USP Class I-VI and US FDA guidance for Intact Skin Surface Devices, RoHS, ¹¹ REACH, PAHs, UL 94, UL 746A, Statement of Composition for Toy Applications		

Ordering information

	HP 3D High Reusability PA 12	HP 3D High Reusability PA 12	HP 3D High Reusability PA 12 Production Material	HP 3D High Reusability PA 12 ^{12, 13, 14}
Product number	V1R10A	V1R16A	V1R34A	V1R20A
Weight	13 kg/28.7 lb	130 kg/286.7 lb	130 kg/286.7 lb	600 kg/1322.8 lb
Capacity	30L ¹⁵	300L ¹⁵	300L ¹⁵	1400L ¹⁵
Dimensions (xyz)	600 x 333 x 302 mm (23.6 x 13.1 x 11.9 in)	800 x 600 x 1205 mm (31.5 x 23.6 x 47.4 in)	800 x 600 x 1205 mm (31.5 x 23.6 x 47.4 in)	1143 x 1143 x 1500 mm (45 x 45 x 59 in)
Printer compatibility	HP Jet Fusion 3D 4210/4200 Printing Solutions	HP Jet Fusion 3D 4210/4200 Printing Solutions	HP Jet Fusion 3D 4210 Printing Solution	HP Jet Fusion 3D 4210 Printing Solution
Fast cooling compatibility	Compatible	Compatible	Compatible	Compatible

Eco Highlights

- Powders and agents are not classified as hazardous¹⁶
- Cleaner, more comfortable workplace—enclosed printing system, and automatic powder management¹⁷
- Minimizes waste due to industry-leading reusability of powder¹⁸

Find out more about HP sustainable solutions at hp.com/ecosolutions

Dynamic security enabled printer. Only intended to be used with cartridges using an HP original chip. Cartridges using a non-HP chip may not work, and those that work today may not work in the future. More at: hp.com/go/learnaboutsupplies

Learn more at hp.com/go/3DMaterials

- Based on internal testing and public data for solutions on market as of April, 2016. Cost analysis based on standard solution configuration price, supplies price, and maintenance costs recommended by manufacturer. Common cost criteria: using HP 3D High Reusability PA 12 material, and the powder reusability ratio recommended by manufacturer, and printing under certain build conditions and part geometries. HP Jet Fusion 3D 4200 Printing Solution average printing cost per part is half the average cost of comparable fused deposition modeling (FDM) and selective laser sintering (SLS) printer solutions from \$100,000 to \$300,000 USD. Cost criteria: printing 1 build chamber per day/5 days per week over 1 year of 30 cm³ parts at 10% packing density. HP Jet Fusion 3D 4210 Printing Solution average printing cost per part is 65% lower versus the average cost of comparable FDM and SLS printer solutions from \$100,000 to \$300,000 USD and is 50% lower versus the average cost of comparable SLS printer solutions for \$300,000 to \$450,000 USD. Cost criteria: printing 1.4 full build chambers of parts per day/5 days per week over 1 year of 30 cm³ parts at 10% packing density on test print mode.
- Tested with diluted alkalis, concentrated alkalis, chlorine salts, alcohol, ether, esters, ketones, aliphatic hydrocarbons, unleaded petrol, motor oil, aromatic hydrocarbons, toluene, and DOT 3 brake fluid.
- Based on HP internal testing, June 2017, HP 3D600/3D700/3D710 Fusing and Detailing Agents and HP 3D High Reusability PA 12 powder meet USP Class I-VI and US FDA's guidance for Intact Skin Surface Devices. Tested according to USP Class I-VI (including irritation, acute systemic toxicity, and implantation; cytotoxicity per ISO 10993-10, biological evaluation of medical devices—part 5: Tests for in vitro cytotoxicity; and sensitization per ISO 10993-10, biological evaluation of medical devices—part 10: Tests for irritation and skin sensitization). It is the responsibility of the customer to determine that its use of the fusing and detailing agents and powder is safe and technically suitable to the intended applications and consistent with the relevant regulatory requirements (including FDA requirements) applicable to the customer's final product. For more information, see www.hp.com/go/3dcompatibilitycertification.
- Compared to selective laser sintering (SLS) and fused deposition modeling (FDM) technologies, HP Multi Jet Fusion technology can reduce the overall energy requirements needed to attain full fusing and reduce the system requirements for large, vacuum-sealed ovens. In addition, HP Multi Jet Fusion technology uses less heating power than SLS systems for better material properties and material reuse rates, minimizing waste.
- Based on using recommended packing densities and compared to selective laser sintering (SLS) technology, offers excellent reusability without sacrificing mechanical performance. Tested according to ASTM D638, ASTM D256, ASTM D790, and ASTM D648 and using a 3D scanner for dimensional accuracy. Testing monitored using statistical process controls.
- HP Jet Fusion 3D Printing Solutions using HP 3D High Reusability PA 12 provide up to 80% post-production surplus powder reusability, producing functional parts batch after batch. For testing, material is aged in real printing conditions and powder is tracked by generations (worst case for reusability). Parts are then made from each generation and tested for mechanical properties and accuracy.
- Compared to selective laser sintering (SLS) technology, tested according to ASTM D638, ASTM D256, ASTM D790, and ASTM D648.
- The following technical information should be considered representative of averages or typical values and should not be used for specification purposes. These values are with FWTATDAG, 15, 18, 11.03 and have been obtained from a sample of specimens printed in plots with 6% packing density and 20% fresh powder. Separation between specimens in the plot was 10 mm. Modulus has been calculated using the slope of the regression line between 0.05% and 0.25% strain measured with an automatic extensometer during the entire test. Cross-section dimension measures using a micrometer with round ends. Conditioning according to ASTM D618 Procedure A. Testing conducted 48 hours after printing and unpacking of the parts at 23° C/73° F and 50% RH. Orientations defined according to ASTM F2797.
- Test results realized under the ASTM D638 with a test rate of 10 mm/min, specimens type I.
- Test results realized under ASTM D790 Procedure B at a test rate of 13.55 mm/min.
- RoHS certification for EU, Bosnia-Herzegovina, China, India, Japan, Jordan, Korea, Serbia, Singapore, Turkey, Ukraine, Vietnam.
- Additional material management equipment is required.
- The SLS is only available for the HP Jet Fusion 3D 4210B Printing Solution.
- This product number is valid directly by HP.
- Liters refers to the materials container size and not the actual materials volume. Materials are measured in kilograms.
- The HP powder and agents do not meet the criteria for classification as hazardous according to Regulation (EC) 1272/2008 as amended.
- Compared to manual print retrieval process used by other powder-based technologies, the term "cleaner" does not refer to any indoor air quality requirements and/or consider related air quality regulations or testing that may be applicable.
- Compared to PA 12 materials available as of June, 2017, HP Jet Fusion 3D Printing Solutions using HP 3D High Reusability PA 12 provide up to 80% post-production surplus powder reusability, producing functional parts batch after batch.

© Copyright 2017–2019 HP Development Company, L.P.

Nothing herein should be construed as constituting an additional warranty. The only warranties for HP products and services are set forth in the express warranty statements accompanying such products and services and/or in a written agreement between you and HP. HP believes that the information herein is correct based on the current state of scientific knowledge and as of the date of its publication, however, to the maximum extent permitted by law HP EXPRESSLY DISCLAIMS ANY REPRESENTATIONS AND WARRANTIES OF ANY KIND, WHETHER EXPRESS OR IMPLIED, AS TO THE ACCURACY, COMPLETENESS, NON-INFRINGEMENT, MERCHANTABILITY AND/OR FITNESS FOR A PARTICULAR PURPOSE (EVEN IF HP IS AWARE OF SUCH PURPOSE) WITH RESPECT TO ANY INFORMATION PROVIDED. Except to the extent that exclusion is prevented by law, HP shall not be liable for technical or editorial errors or omissions, and damages or losses of any kind or nature that result from the use of or reliance upon this information, which is subject to change without notice. The HP Jet Fusion 3D products have not been designed, manufactured or tested by HP for compliance with legal requirements for specific 3D printed parts and their uses, and recipients are responsible for determining the suitability of HP Jet Fusion 3D products for their uses, ensuring compliance with applicable laws and regulations, and being aware that other safety or performance considerations may arise when using, handling or storing the product.

4A46-4895ENA, February 2019

This is an HP Indigo digital print.



APPENDIX D

3D Hubs case study of Multijet Fusion vs SLS



	MJF	SLS
Cost for one-off part	Average: \$46.28 Minimum: \$25.71	Average: \$46.45 Minimum: \$26.79
Cost per part for 30 parts	Average: \$28.75 Minimum: \$19.00	Average: \$25.85 Minimum: \$19.48
Lead time	Average: 4 days Top hub: 2.9 days	Average: 7 days Top hub: 5.2 days

Appendix D

(3Dhubs, 2019)

APPENDIX E

Proof of HP Multijet Fusion vs SLS printer

1. Based on internal testing and public data, HP Jet Fusion 3D 4210 Printing Solution average printing cost-per-part is 65% lower versus the average cost of comparable fused deposition modeling (FDM) and selective laser sintering (SLS) printer solutions from \$100,000 USD to \$300,000 USD on market as of April, 2016 and is 50% lower versus the average cost of comparable SLS printer solutions for \$300,000 USD to \$450,000 USD. Cost analysis based on: standard solution configuration price, supplies price, and maintenance costs recommended by manufacturer. Cost criteria: printing 1.4 full build chambers of parts per day/5 days per week over 1 year of 30 cm³ parts at 10% packing density on fast print mode under certain build conditions and part geometries using HP 3D High Reusability PA 12 material, and the powder reusability ratio recommended by manufacturer.
2. Based on internal testing and simulation, HP Jet Fusion 3D average printing time is up to 10 times faster than average printing time of comparable fused deposition modeling (FDM) and selective laser sintering (SLS) printer solutions from \$100,000 USD to \$300,000 USD on market as of April, 2016. Testing variables for the HP Jet Fusion 4210/4200 Printing Solutions: Part quantity: 1 full build chamber of parts from HP Jet Fusion 3D at 20% of packing density versus same number of parts on above-mentioned competitive devices; Part size: 30 cm³; Layer thickness: 0.08 mm/0.003 inches.
3. Industry-leading surplus powder reusability based on using HP 3D High Reusability PA 12 at recommended packing densities and compared to selective laser sintering (SLS) technology, offers excellent reusability without sacrificing mechanical performance. Tested according to ASTM D638, ASTM D256, ASTM D790, and ASTM D648 and using a 3D scanner for dimensional accuracy. Testing monitored using statistical process controls.
4. Based on HP's unique multi-agent printing process. Excellent dimensional accuracy and fine detail within allowable margin of error. Based on dimensional accuracy of ± 0.2 mm/0.008 inches on XY for hollow parts below 100 mm/3.94 inches and $\pm 0.2\%$ for hollow parts over 100 mm/3.94 inches, using HP 3D High Reusability PA 12 material, measured after sandblasting. See hp.com/go/3Dmaterials for more information on materials specifications.
5. Based on the following mechanical properties: Tensile strength at 48 MPa (XYZ), Modulus at 1700 -1800 MPa (XYZ). ASTM standard tests with HP 3D High Reusability PA 12 material. See hp.com/go/3Dmaterials for more information on materials specifications.
6. Fast Cooling is enabled by HP Jet Fusion 3D Processing Station with Fast Cooling and is recommended only for HP 3D High Reusability PA 12 and HP 3D High Reusability PA 12 Glass Beads. HP Jet Fusion 3D Processing Station with Fast Cooling accelerates parts cooling time vs recommended manufacturer time of selective laser sintering (SLS) printer solutions from \$100,000 USD to \$450,000 USD, as tested in April, 2016. Fused deposition modeling (FDM) not applicable. Continuous printing requires an additional HP Jet Fusion 3D build unit (standard printer configuration includes one HP Jet Fusion 3D build unit).
7. Compared to manual print retrieval process used by other powder-based technologies. The term "cleaner" does not refer to any indoor air quality requirements and/or consider related air quality regulations or testing that may be applicable. The HP powder and agents do not meet the criteria for classification as hazardous according to Regulation (EC) 1272/2008 as amended.
8. This SKU is only available for the HP Jet Fusion 3D 4210B Printing Solution.
9. This product number is sold directly by HP.
10. This product is only available in Europe and in the Americas.
11. Liters refers to the materials container size and not the actual materials volume. Materials are measured in kilograms.
12. Additional material management equipment is required.
13. Available during the second half of 2019.
14. For latest technical specifications, please visit hp.com/go/3DPrint.
15. Based on 0.08-mm (0.003-in) layer thickness and 7.55 sec/layer.
16. The HP Jet Fusion 3D Printing Solution should be connected to the HP Cloud in order to enable the correct functioning of the printer and to offer better support.
17. Compared to PA 12 and PA 11 materials available as of June, 2017, HP Jet Fusion 3D Printing Solutions using HP 3D High Reusability PA 12 provide up to 80% post-production surplus powder reusability and HP Jet Fusion 3D Printing Solutions using HP 3D High Reusability PA 11 provide up to 70% post-production surplus powder reusability, producing functional parts batch after batch.
18. Printing supplies eligible for recycling vary by printer. Visit hp.com/recycle to see how to participate and for HP Planet Partners program availability; program may not be available in your area. Where this program is not available, and for other consumables not included in the program, consult your local waste authorities on appropriate disposal.

Appendix E

(HP, 2019)

APPENDIX F

PA12 Mass

PROPERTIES	
Part Number	Helicopter_Floor_solid
Part Name	Helicopter_Floor_solid v3
Description	
Area	5.510E+05 mm ²
Density	0.001 g / mm ³
Mass	5785.459 g
Volume	5.166E+06 mm ³

Aluminium Mass

PROPERTIES	
Part Number	Helicopter_Floor_solid
Part Name	Helicopter_Floor_solid v3
Description	
Area	5.510E+05 mm ²
Density	0.003 g / mm ³
Mass	1.395E+04 g
Volume	5.166E+06 mm ³

Appendix F Mass of PA12 & Aluminium Autodesk Fusion 360 model