Technologies series

3D Printing

Complex supply chains, traditional manufacturing, and product designs all stand to be transformed

Manufacturing's next dimension

What it is

3D printing (3DP), also known as Additive Manufacturing (AM), refers to the automated creation of a three-dimensional object from a digital file.

How it works

A 3D object is designed using specialist software that creates a computer-aided design (CAD) file that slices the 3D digital object into layers, which in turn are read by the printer software.[1] A 3D printer then reads this file and creates the object, layer by layer.[2]

At its simplest, this can involve layering material(s) sequentially, either with or without an adhesive between the layers. More complex techniques involve creating a structure from powder or liquid, by either melting or fusing material using lasers, electron beams, or UV light. Although heat-sensitive plastics are the most commonly used, materials range from ceramics to titanium powder, in applications from jet engines to bone replacements.[3]

Applications

3DP-use groups into seven broad categories, according to the processes and materials used.[4] Currently, the most common application of 3DP is in rapid prototyping: it is used by product designers, architects, and engineers who require fast turnaround at the design stage.[5] But the range of uses is expanding rapidly. Two examples illustrate the potential of this technology:

- **Aerospace manufacturing.** The printing of jet engine and rocket parts;[6] and the printing of spare parts in orbit, on the International Space Station (ISS).[7]
- **Healthcare**. In addition to prosthetics[8] and implants,[9] 3DP has applications in medical training,[10] and most recently in the manufacture of medical equipment in response to the SARS-CoV2 pandemic.[11]

Implications and issues

Although still only a small proportion of manufacturing,[12] 3DP is moving rapidly towards more widespread industrial application, as demonstrated by its growing market.[13] So far the UK, Germany, and the US have led the field over this past decade,[14] but most recently investment in Asia has been rising rapidly,[15] particularly in China.[16]

Many companies are seeking to shorten supply chains, and some wish to reduce dependence on China.[17] Moreover, the pandemic has highlighted the world's reliance on fragile,[18] just-in-time supply chains.[19] By offering more localised manufacturing 3DP has considerable potential to help solve these issues. For example, 3DP has the potential to reduce greenhouse gas emissions both through lower material use and shortened supply chains,[20] helping towards a circular economy.[21] More generally, whereas many structures are optimised for manufacture as opposed to function,[22] 3DP is not limited by tooling:[23] Complex and innovative designs can be created easily.[24]

That said, various issues will remain for some time yet:

1. **High costs.** 3DP cannot yet match the costs of mass-production manufacturing.[25] Innovation in materials,[26] automation,[27] and simplified logistics could however offset this.
2. **Expertise.** The skills required are not widespread – further investment will be required.[28]
3. **Lifespan.** Imperfections during the manufacturing process can lead to a shorter lifespan than for traditionally manufactured parts, although innovation here is moving quickly.[29]
4. **Intellectual property.**[30] Copyright becomes difficult to enforce once it is possible to transmit data online – as seen in the music and movie industries.[31]
5. **Weapons.** The ability to print a working firearm at home renders gun control near impossible.[32]

With the vulnerabilities of existing structures of production and ways of doing things now firmly centre stage, disruption from 3DP – including from a (pre-COVID) estimated 40% reduction in trade volumes by 2060 – stands to come on stream more quickly and become more far reaching.[33] ■

[1] Dating from the 1980s, 3D printing has evolved considerably, but the fundamentals remain the same. For a detailed overview of the principles behind 3D printing/Additive Manufacturing, see 3D Hubs 2020. T*he basics - What is 3D printing?* 3D Hubs [online] Available at: <https://www.3dhubs.com/guides/3d-printing/#basics> [Accessed 6 January 2021].

[2] This is in fundamental contrast to traditional subtractive manufacturing, in which a part is manufactured by successively removing layers of material until only the desired object remains.

[3] The three largest customers of the 3DP/AM industry, comprising roughly 15% each, are the automotive; consumer & electronics; and aerospace sectors, in descending order. While much more important to it, the medical industry comprises a smaller part of the market than any of those three. See, Masuch, T., 2020. *Consumer Products & Electronics Increasingly Important For Am Market*. Formnext Magazine [online] Available at: <https://fon-mag.de/industry-news/2020/05-wohlers-report> [Accessed 6 January 2021].

[4] Briefly, these are: 1. Vat Photopolymerisation, 2. Material Extrusion, 3. Material Jetting, 4. Binder Jetting, 5. Powder Bed Fusion, 6. Direct Energy Deposition, and 7. Sheet Lamination. Each of these has further subcategories, with each generally developed and run by an individual company, and for particular applications.

For an overview of the technologies, processes, and materials used in 3D printing, see 3D Hubs, 2020. *3D Printing Processes*. 3Dhubs [online] Available at: < https://www.3dhubs.com/guides/3d-printing/#technologies> [Accessed 6 January 2021] and for a visual overview see the following infographic, 3D Hubs, 2016. *Additive Manufacturing technologies to watch out for in 2017*. medium.com [online] Available at: <https://miro.medium.com/max/3780/1*UT6mgla-hp6_z2Hh0JWk5w.png> [Accessed 6 January 2021].

[5] This means that the design process can be speeded up, reducing the time from conception to release of a product.

[6] 3DP has been used across the aerospace industry, but is best exemplified by the fuel nozzle that General Electric developed for their LEAP jet engine, which has sold over 30,000 units over the past few years. 3D printing this fuel nozzle reduced the number of parts required from 20 to 1, which led to a 60% reduction in price and, most importantly for an aeroplane part, a 40% reduction in weight. 3DP has notably been used in the rocket thrusters of SpaceX's Dragon Capsule. See, GE Additive, 2018. *New manufacturing milestone: 30,000 additive fuel nozzles*. GE [online] Available at: <https://www.ge.com/additive/stories/new-manufacturing-milestone-30000-additive-fuel-nozzles> [Accessed 6 January 2021] and Staff, 2014. *SpaceX SuperDraco Thruster Features A 3D Printed Engine Chamber*. engineering.com [online] Available at: <https://www.engineering.com/3DPrinting/3DPrintingArticles/ArticleID/7665/SpaceX-SuperDraco-Thruster-Features-A-3D-Printed-Engine-Chamber.aspx> [Accessed 6 January 2021].

[7] Given the cost of rocket launches, it is highly expensive to keep the International Space Station (ISS) stocked with parts and spares, and far too expensive to consider extending this approach for further space exploration. It would be orders of magnitude cheaper to launch a 3D printer and manufacture any required parts once already in space. NASA has already adopted the approach for plastic parts required on the ISS. See, Hornick, J.F., 2016. *3D Printing Our Way to the Stars*. Finnegan [online] Available at: <https://www.finnegan.com/en/insights/articles/3d-printing-our-way-to-the-stars.html> [Accessed 6 January 2021].

[8] Although not often thought of as a such, hearing aids are prosthetics, and the entire industry has shifted to 3DP. This is because every ear is unique, and so every hearing aid must be too. Prior to 3DP, custom creation required silicon moulds, a labour-intensive and imperfect process. See, Brans, K., 2013. 3D Printing, a Maturing Technology. *IFAC Proceedings Volumes* [e-journal] Available at: https://doi.org/10.3182/20130522-3-BR-4036.00112.

[9] See, Sepping, S., 2018. *Human Organ Printing*. Llewellyn Consulting. Available on request.

[10] Including anatomical models used for medical education and surgical rehearsal, as well as surgical guides custom made for each patient, so as to reduce the likelihood of surgeon error and patient swelling. See, Redwood, B., *Medical 3D printing applications*. 3Dhubs [online] Available at: <https://www.3dhubs.com/knowledge-base/medical-3d-printing-applications> [Accessed 6 January 2021].

[11] These include nasal swabs for tests, facemasks and shields, mask and ventilator filters, and even entire ventilators. Although impressive, there are risks associated with using such parts, as they have not proceeded through the stringent testing processes traditionally required for such equipment. Ensuring that products are sufficiently sterile is another issue. Moreover, the requirements of budget-constrained healthcare providers are outpacing the speed of current 3DP manufacturing. However, this rapid response also illustrates an important principle of 3DP, that

'retooling' a 3DP factory to produce entirely different goods takes only as long as it takes to download the files to print them. See, Tino, R., et al. 2020. COVID-19 and the role of 3D printing in medicine. *3D Print Med*. Available at: https://doi.org/10.1186/s41205-020-00064-7, Metal AM, 2020. *The global Additive Manufacturing community responds to coronavirus*. MetalAM [online] Available at: <https://www.metal-am.com/the-global-additive-manufacturing-community-responds-to-coronavirus/> [Accessed 6 January 2021], and Gallagher, M. B., 2020. *3 Questions: The risks of using 3D printing to make personal protective equipment*. MIT [online] Available at: <https://news.mit.edu/2020/3q-risks-using-3d-printing-make-personal-protective-equipment-0326> [Accessed 6 January 2021].

[12] World manufacturing contributes approximately $14tn to the global economy, $12bn of which was linked with additive manufacturing. See, Endnote 12 and World Bank, 2020. Manufacturing, value added (current US$). The World Bank [online] Available at: <https://data.worldbank.org/indicator/NV.IND.MANF.CD> [Accessed 6 January 2021].

[13] Estimates of the 3DP/AM industry show that it expanded by 21% in 2019, to almost $12bn, a slightly slower pace of growth than the previous year. See, McCue, T.J., 2020. *Additive Manufacturing Industry Grows To Almost $12 Billion In 2019*. Forbes [online] Available at: <https://www.forbes.com/sites/tjmccue/2020/05/08/additive-manufacturing-industry-grows-to-almost-12-billion-in-2019> [Accessed 6 January 2021] and Goehrke, S., 2019. *Why Are Investors Pouring Millions Into 3-D Printing?* Forbes [online] Available at: <https://www.forbes.com/sites/sarahgoehrke/2019/01/25/why-are-investors-pouring-millions-into-3-d-printing> [Accessed 6 January 2021].

[14] North America dominates in terms of intellectual property, and level of investment in 3DP, but lacks in terms of governmental support or industrial policy. Europe counts the largest number of 3DP companies, and the UK and Germany are notable in having clear industrial strategies supporting 3DP. See: AMFG, 2019. *Additive Manufacturing Around the World: What is the State of 3D Printing Adoption in North America and Europe?* Autonomous Manufacturing [online] Available at: <https://amfg.ai/2019/11/07/additive-manufacturing-around-the-world-what-is-the-state-of-3d-printing-adoption-in-north-america-and-europe> [Accessed 6 January 2021].

[15] Although most intellectual property, and the majority of 3DP companies, are in North America and Europe, hands-on experience of 3DP has expanded the most dramatically in South Korea and China. See, Steinberg, G., and Karevska, S., 2019. *How 3DP is moving from hype to game changer*. EY [online] Available at: <https://www.ey.com/en_gl/advisory/how-3dp-is-moving-from-hype-to-game-changer> [Accessed 6 January 2021].

[16] China has made the development of its 3DP industry a national priority, and is funding it accordingly. See, Hcaria, R., 2017. *China State Action Plan Aims To Make 3D Printing Worth $3 Billion By 2020*. 3D Printing Industry [online] Available at: <https://3dprintingindustry.com/news/china-action-plan-3d-printing-3-billion-2020-126119/> [Accessed 6 January 2021].

[17] Increasing labour costs and tariffs have also played a role in companies moving manufacturing out of China, prior to the SARS-CoV2 pandemic. See, Van den Bossche, P., et al., 2020. *US Reshoring Index*. Kearney [online] Available at: <https://www.kearney.com/operations-performance-transformation/us-reshoring-index/full-report> [Accessed 6 January 2021].

[18] In response to the SARS-CoV2 pandemic Japan has included a clause in its financial stimulus package to fund the move of manufacturing out of China. See, Nakamura, K., 2020. *Japan to help shift manufacturing to ASEAN from China after virus disrupts supply chains*. The Japan Times [online] Available at: <https://www.japantimes.co.jp/news/2020/05/05/business/japan-manufacturing-asean-china-coronavirus-supply-chains> [Accessed 6 January 2021].

[19] This fact has been well appreciated by many, from individuals trying to source personal protection such as masks to companies with supply chains that have been halted through reliance on a single vendor. See, Linton, T., and Vakil, B., 2020. *Coronavirus Is Proving We Need More Resilient Supply Chains*. Harvard Business Review [online] Available at: <https://hbr.org/2020/03/coronavirus-is-proving-that-we-need-more-resilient-supply-chains> [Accessed 6 January 2021].

[20] Although 3DP uses by-product from traditional manufacturing processes as its input, and uses less material overall when compared with subtractive manufacturing, it can still be quite demanding in terms of energy usage and environmental impact. See, Peng, T., Kellens, K., Tang, R., Chen, C., & Chen, G. (2018). Sustainability of additive

manufacturing: An overview on its energy demand and environmental impact. *Additive Manufacturing*, https://doi.org/10.1016/j.addma.2018.04.022 and AMFG, 2020. *How Sustainable is Industrial 3D Printing?* Autonomous Manufacturing [online] Available at: <https://amfg.ai/2020/03/10/how-sustainable-is-industrial-3d-printing> [Accessed 6 January 2021].

[21] For discussion of the potential of 3DP to contribute to a circular economy. See, Despeisse, M., et al., 2017. Unlocking value for a circular economy through 3D printing: A research agenda. *Technological Forecasting and Social Change* [e-journal] Available at: <https://doi.org/10.1016/j.techfore.2016.09.021> [Accessed 6 January 2021].

[22] Designing a product for optimised performance under defined conditions, rather than for manufacture, is called 'topology optimisation'. This can lead to dramatic reductions in weight and simultaneous increases in strength for a part. For medical implants this can also involve optimising a bone implant for better integration with the patient's existing bone, leading to better healing and performance. See, AMFG, 2018. *How Topology Optimisation and 3D Printing Unlock New Design Opportunities*. Autonomous Manufacturing [online] Available at: <https://amfg.ai/2018/04/19/topology-optimisation-additive-manufacturing> [Accessed 6 January 2021] and Wasserman S., 2015. *3D Printing Brings Out the Full Potential of Topology Optimization*. engineering.com [online] Available at: <https://www.engineering.com/DesignSoftware/DesignSoftwareArticles/ArticleID/11008/3D-Printing-Brings-Out-the-Full-Potential-of-Topology-Optimization.aspx> [Accessed 6 January 2021].

[23] 3DP can also augment traditional manufacturing methods through the production of customised moulds, jigs, and machine parts. Alteration of machines and moulds in traditional manufacturing is a large investment, 3DP lowers this cost dramatically, given that altered parts can be manufactured cheaply, allowing for the recouping of costs from the investment in a 3D printer and extending the lifespan of a traditional machine. See, AMFG, 2019. *5 Ways 3D Printing Complements Traditional Manufacturing*. Autonomous Manufacturing [online] Available at: <https://amfg.ai/2019/12/19/5-ways-3d-printing-complements-traditional-manufacturing> [Accessed 6 January 2021].

[24] This can result in both more complex and simplified designs simultaneously: more complex in terms of the interior detailing of a part which would otherwise be unreachable with traditional tools; but simplified in terms of how many individual parts are created and assembled. This is exemplified by the work at GE Manufacturing, who reduced the number of parts required for a helicopter engine from 900 separate components to just 16. See, Kellner, T., 2017. *An Epiphany Of Disruption: GE Additive Chief Explains How 3D Printing Will Upend Manufacturing*. GE Reports [online] Available at: <https://www.ge.com/reports/epiphany-disruption-ge-additive-chief-explains-3d-printing-will-upend-manufacturing/> [Accessed 6 January 2021].

[25] 3D printers are still expensive, particularly those that are capable of creating large metal parts. To fit a factory floor with them costs far more than a floor of CNC machines. This cost is not rapidly defrayed either: this means that investors have to be particularly sure about the appropriateness of their decision.

[26] Polymers are the most popular materials for 3DP, due primarily to their large installed base of existing 3D printers and the ease of use. Metals are increasing in popularity, but creating the metal powder specifically for 3DP is a factor of 10 more expensive than materials used in conventional manufacturing processes – although this has more than halved in 5 years. Different processes and equipment are required for each metal, and many industries have requirements regarding metal purity, such that a reaction chamber has to be dedicated to producing one type of atomised metal powder. See, AMFG, 2019. *The Evolution of 3D Printing Materials Market: Trends and Opportunities in 2019.* Autonomous Manufacturing [online] Available at: <https://amfg.ai/2019/11/21/the-evolution-of-3d-printing-materials-market-trends-and-opportunities-in-2019> [Accessed 6 January 2021] and Küpper, D., 2019. *Surviving Disruption in Additive Manufacturing*. Boston Consulting Group [online] Available at: <https://www.bcg.com/publications/2019/surviving-disruption-additive-manufacturing.aspx> [Accessed 6 January 2021].

[27] The production speed of 3D printed parts can sometimes be misleading. Although certain processes, such as vat photopolymerisation, can create well-finished parts, most 3D-printed parts require some degree of post-production finishing work. This can lead to overall production times comparable with traditional manufacturing processes. In order to compete with traditional manufacturing methods and to realise some of the potential advantages of 3DP. a higher level of automation is required, both at the process and management software level. See, Molitch-Hou, M., 2018. *Automated 3D Printing: How Industrial Additive Manufacturing Is Evolving*. Engineering.com [online] Available at: <https://www.engineering.com/3DPrinting/3DPrintingArticles/ArticleID/16626/Automated-3D-Printing-How-Industrial-Additive-Manufacturing-Is-Evolving.aspx> [Accessed 23 July 2020].

[28] According to a 2018 paper published by CECIMO, the European Association of the Machine Tool Industry and related Manufacturing Technologies, the skills shortage was one of the largest obstacles to growth of the technology in the EU. This is linked both to the paucity of dedicated easy-to-use 3D printing software solutions and a mismatch between traditional design expertise and that required for additive manufacturing. See, Cecimo, 2018. *Activities Report 2018*. European Association of the Machine Tool Industry and related Manufacturing Technologies [online] Available at: <https://www.cecimo.eu/wp-content/uploads/2019/03/AM-Activities-Report-2018.pdf>[Accessed 6 January 2021].

[29] This is in part due to the way that it is manufactured, forming a grain along the direction of formation and vertically in line with the material bed, much as wood forms a vertical grain, along which it is easily split. Researchers have also observed imperfections in the formation of parts using binder jetting, whereby lasers solidify a metal powder, - with the lack of support from the powder bed leading to increased porosity in 3DP manufactured parts. See, Sun, T., et al., 2019. Real time observation of binder jetting printing process using high-speed X-ray imaging. *Scientific Reports*, [e-journal] Available at: https://doi.org/10.1038/s41598-019-38862-7. While newer 3DP technologies aim to solve these problems, and several companies have done so in innovative ways, other 3DP parts may still meet quality demands despite slight imperfections, depending on the application. Furthermore, several 3DP parts have been used in high-stress scenarios such as in rocket thrusters and jet turbines. See, Carbon, 2020. *Digital Light Synthesis™*. Carbon3d [online] Available at: <https://www.carbon3d.com/our-technology/> [Accessed 6 January 2021] and DesktopMetal. *Production System™*. DesktopMetal [online] Available at: <https://desktopmetal.com/products/production> [Accessed 6 January 2021] and AMFG, 2019. A*pplication Spotlight: 3D-Printed Rockets and the Future of Spacecraft Manufacturing*. Autonomous Manufacturing [online] Available at: <https://amfg.ai/2019/08/28/application-spotlight-3d-printed-rockets-and-the-future-of-spacecraft-manufacturing> [Accessed 6 January 2021].

[30] This is regarded as the key reason why 3DP printing has experienced a renaissance. Upon the expiration of key patents relating to 3DP processes, prices for 3D printers dropped from $10,000 to $1,000, ushering in consumer grade printers for <$300. See, Schoffer, F., 2016. *How expiring patents are ushering in the next generation of 3D printing*. TechCrunch [online] Available at: <https://techcrunch.com/2016/05/15/how-expiring-patents-are-ushering-in-the-next-generation-of-3d-printing> [Accessed 6 January 2021].

[31] There is currently no specific legislation that addresses 3DP infringements. It is likely that, even with judicious application of Digital Rights Management (DRM), that designs will be shared online using peer-to-peer (P2P) networks. The example of iTunes and Spotify demonstrate that only when using these services is sufficiently cheap and streamlined will they overtake P2P. However, the dynamics may well differ when dealing with tangible objects as can be 3D printed, as opposed to intangible experiences such as music or film. The EU has recently released a report on IP and 3DP with recommendations concerning the regulation of the industry. See, Essop, A., 2020. *Analysis of The Eu Report On 3D Printing Ip With Marks & Clerk*. 3D Printing Industry [online] Available at: <https://3dprintingindustry.com/news/analysis-of-the-eu-report-on-3d-printing-ip-with-marks-clerk-171495> [Accessed 6 January 2021]. For a further discussion see, Henry, M., 2018. *How 3D Printing Challenges Existing Intellectual Property Law*. Henry Patent Law Firm [online] Available at: <https://www.henrypatentfirm.com/blog/3d-printing-challenges-patent-law> [Accessed 6 January 2021] and for suggestions for anti-copying technology see, Hornik, J., 2018. *Anti-Copying Technology for 3D Printing: A Survey*. 3D Print.com [online] Available at: <https://3dprint.com/215217/anti-copying-technology/> [Accessed 6 January 2021].

[32] In 2013, the company Distributed Defense released blueprints for the creation of a wholly 3D-printed firearm from plastic – the 'Liberator'. This was supposedly designed as an exercise in 2nd Amendment rights, and the details have since been shared online. The company has recently relaunched with a "Netflix for blueprints" plan whereby U.S. citizens are able to pay a $50 annual subscription for access to plans. While this is a significant development, to date at least these weapons have proved to be unstable, which limits their use, for the moment at least. See: Forrest, B., 2020. *Gun-Rights Activist Releases Blueprints for Digital Guns*. Wall Street Journal [online] Available at: <https://www.wsj.com/articles/gun-rights-activist-releases-blueprints-for-digital-guns-11585414671> [Accessed 6 January 2021].

[33] The effects on logistics has the potential to be far-reaching and hugely disruptive with ING estimating an attention-grabbing 40% reduction in trade volumes by 2060 in a scenario of high uptake of the technology. However, there are uncertainties, this will be interpreted differently by different companies with both many opportunities and challenges. A World Bank case study analysed the effect on trade when the hearing aid industry switched to ~100% 3DP production. They found that the trade volume increased due to reduced production costs which

predominantly benefitted middle- and upper-income countries who had invested in 3DP technology relatively early. However, although there are other products which could follow a similar trajectory many other are limited by their weight or bulk and therefore benefit from localised production. See, Freund, C., Mulabdic, A., Ruta, M., 2019. *Is 3D Printing a Threat to Global Trade?* World Bank Group [online] Available at: <hhttps://openknowledge.worldbank.org/handle/10986/32453> [Accessed 6 January 2021] and Leering, R., 2017. *3D printing: a threat to global trade*, ING [online] Available at: <https://www.ingwb.com/media/2088633/3d-printing-report-031017.pdf> [Accessed 6 January 2021].