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**Thematic Research:** Technology

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# 3D Printing

27 August 2019

## Has 3D printing come of age?

3D printing is in its mid-thirties and is now approaching market growth that Chuck Hull could only have dreamt about when he invented it in 1983.

By 2025, 3D printing, or additive manufacturing, will be a $32bn industry, rising to over $60bn by 2030. The compound annual growth rate (CAGR) between 2018 and 2025 will be 16%, according to GlobalData estimates, with software growing slightly faster than hardware, materials and services.

Yet behind the optimism, competition and casualties are increasing: UK powder maker Metalysis recently went into administration before being rescued by Power Resources, a mining company; SLM Solutions, a German manufacturer of 3D metal printers, had a poor first half of 2019, selling a third of the machines it sold in the first half of 2018 with revenues down 45%; and Organovo is considering its strategic options after biological performance issues with its 3D-printed liver tissues.

3D printing has always been most closely associated with prototyping and short production runs. But now it is becoming a key part of the manufacturing mix alongside injection molding and computer numerical control machining. The use of polymers – particularly plastics – in 3D printing still exceeds metals, but the gap is narrowing, and metals could outstrip polymers from 2021.

Healthcare is a strong adopter, with applications from medical training to the operating table. Great Ormond Street Hospital's use of 3D printed models for an operation to separate twins joined at the head has increased awareness. The industry's growth has led to chemicals giants like BASF and Henkel driving the creation of new materials.

4D printing – where 3D printed objects transform their shape in response to an external stimulus, such as heat or moisture – also offers potential.

## Who are the leading 3D printing companies?

We split the 3D printing value chain into four segments: hardware, materials, software and services. Below, we highlight some of the leading companies in each of these segments:

- **Hardware:** Desktop Metal, GE Additive, Markforged, EOS, HP, 3D Systems, Ultimaker, EnvisionTEC, Stratasys
- **Materials:** BASF, Henkel, GKN, Sandvik, Solvay, Höganäs
- **Software:** Siemens, Autodesk, Dassault Systèmes, Materialise, PTC
- **Services:** Optomec, GE Additive, Shapeways, Siemens, Sculpteo

## Which industries are at risk of disruption?

Our research shows that the industries at most risk of disruption over the next five years include aerospace, healthcare, consumer goods, and construction.

## Inside

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# Players

The 3D printing sector has four main categories of players: hardware companies, materials companies, software companies, and services providers. The table below shows some of the leading names in 3D printing under these classifications.

**Who are the leading players in the 3D printing sector?**
And where do they sit in the 3D printing tech stack?

| 3D Printing Tech Stack | | Leaders | | Challengers | |
|---|---|---|---|---|---|
| Hardware | Metal | HP<br>GE Additive<br>3D Systems | Desktop Metal<br>Markforged<br>EOS | Stratasys<br>Renishaw<br>Carbon<br>SLM Solutions | Ultimaker<br>Protolabs<br>ExOne<br>Optomec |
| | Plastic | Stratasys<br>3D Systems<br>EnvisionTEC | HP<br>Carbon<br>Ultimaker | Formlabs<br>Prodways<br>Voxeljet | Markforged<br>EOS<br>XYZprinting |
| | Bio | Organovo<br>EnvisionTEC<br>Cyfuse Biomedical | 3D Bioprinting<br>Regenovo Biotech<br>Aspect Biosystems | BioBots<br>Rokit Healthcare<br>Cellink | |
| Materials | Metals, plastics and ceramics | GKN<br>BASF<br>Henkel | Solvay<br>Höganäs<br>Sandvik | Evonik<br>Stratasys<br>Voestalpine | Arkema<br>Mitsubishi Chemical<br>EOS |
| Software | CAD | Autodesk<br>Dassault Systèmes<br>3D Systems | SketchUp<br>TurboCAD<br>PTC | Ansys<br>Paramatters | |
| | Workflow Management | Adobe<br>Materialise<br>Autodesk | Stratasys<br>AMFG<br>Siemens | Authentise<br>3YourMind | |
| | Slicing Software | Ultimaker (Cura)<br>Simplify3D<br>KISSslicer | Repetier<br>Slicr<br>OctoPrint | Raise3D (ideaMaker)<br>Autodesk (Netfabb)<br>IceSL | |
| | Digital Twins | Siemens<br>Dassault Systèmes<br>PTC | IBM<br>GE Additive<br>Ansys | | |
| Services | Consulting | Materialise<br>3D Systems<br>GE Additive | HP<br>Stratasys<br>Siemens | EY<br>Tata Consultancy Services<br>EOS | |
| | Marketplaces | Turbosquid<br>Pinshape<br>Sculpteo | Thingiverse<br>GrabCAD<br>MyMiniFactory | Etsy | |
| | On demand | iMaterialise<br>Shapeways<br>Sculpteo | Protolabs<br>Voodoo Manufacturing<br>Quickparts (3D Systems) | Stratasys Direct | |
| | Repairs & maintenance | Optomec<br>Stratasys<br>3D Systems | HP<br>GE Additive<br>EOS | | |

Source: GlobalData

# Technology briefing

The 3D printing industry has come a long way since 1983 when Chuck Hull, co-founder of 3D Systems, created the first-ever 3D printed part. It still has a long way to go. Hull's invention led to the creation of an industry that has, until recently, been used primarily for prototyping purposes. Recent years have seen its disruptive influence growing and 3D printing is increasingly being used in the creation of final products.

3D printing technology, coupled with better knowledge of its potential in the economics of manufacturing, has applications in a growing range of products, ranging from the largest industries to the smallest personal products, from jet engines to custom-designed underwear, from tailored running shoes to life-saving living tissue. Ultimately, it even has the potential to disrupt and transform the entire manufacturing industry supply chain.

The techniques, not to mention the science behind 3D – and now 4D – printing, are still developing, as is AM's relationship with subtractive manufacturing and injection molding. Increasingly too, the development of materials technologies – from polymers to metals – will have a fundamental impact on the growth of this industry. It is an illustration of the potential of 3D printing that a number of chemicals companies are weighing in with developments of their own across the board in materials technologies, an intervention that is itself providing a spur to 3D printing's development. Those materials considerations – and the science behind them – are also covered in this section of the report. Before that, we will consider the various approaches to 3D printing.

## Definition

3D printing, also known as additive manufacturing (AM), is the process of joining materials to make objects from three-dimensional model data, typically created layer upon layer. This contrasts with subtractive manufacturing, in which parts of a block of material are selectively removed. Most AM systems will make use of a digital blueprint created by 3D computer-aided design (CAD) software, of which there are several versions in use.

## The eight different types of 3D printing technology

Rather than utilize a single technology, 3D printing uses a range of techniques specific to different printers with different characteristics. They are also provided by 3D printing companies which typically have their own modifications – and distinct terminology – for the technologies. However, all of them are grounded in the concept of additive rather than subtractive technology, with items built up one layer at a time. Some vendors believe that in future, the application will define the process. For example, binder jetting is more useful for less demanding applications with less complexity and higher volumes.

**There are eight primary technologies within the 3D printing industry**

Material extrusion is the cheapest and most popular

| Type of material | 3DP Technology | Description | End market | Starting price* | Build Material |
|---|---|---|---|---|---|
| Solid | Material Extrusion | Force through nozzle | Consumer, autos, medical | $200 | Polymers (esp. plastics) |
| | Direct Metal Deposition | Melt and fuse together | Aerospace, military, autos | $165,000 | Metals |
| Powder | Powder Bed Fusion | Fuse powder with a laser | Aerospace, military, autos | $100,000 | Polymers and metals |
| | Binder jetting | Bond powder with glue | Consumer, electronics | $10,000 | Polymers and metals |
| Liquid | Material jetting | Jet droplets and harden | Product designers | $15,000 | Polymers (esp. plastics) |
| | Vat photopolymerisation | Harden liquid with light | Autos, medical | $10,000 | Polymers (esp. plastics) |
| Sheet | Sheet lamination | Glue sheets and cut | Architecture, education | $5,000 | Plastics, sheet metals |
| Living cells | Bioprinting | Deposit layers of cells | Medical | $10,000 | Biomaterials |

* Starting prices are accurate as at 31 July 2019

Source: GlobalData

Until relatively recently, polymers were the most popular material. That has begun to change, with metal 3D printing starting to take off to such a degree that many in the industry see a crossover point sometime in the next two years when metals will account for the greater share of 3D printing. There are, however, those in the vendor community who believe that crossover point may still be a little while away from taking place, with continued development in polymers taking precedence.

## Material extrusion

Also known as fused deposition modelling (FDM), fused filament fabrication (FFF) or plastic jet printing.

Material extrusion is the simplest, cheapest, and most popular AM technology. It is also the one most likely to take off with consumers. 3D Systems made an extrusion range called Cube, whilst Stratasys has the MakerBot Replicator range. Cheaper imitations of these classic models are available from as little as $200. Industrial grade material extrusion systems, by contrast, start at around $10,000.

The build material for these systems is typically a filament of thermoplastic, coiled onto a spool. The material is melted and then selectively dispensed through a nozzle, much like an automated version of a hot glue gun. As the melted material is forced through the nozzle, the extrusion head (i.e. the platform the object is being built on) moves in the x-y plane.

After a layer is completed, the print head moves up (or the build platform moves down) and the next layer is extruded and adhered to the previous layer. The choice of build materials is limited to polymers and waxes. 3D printers of this type represent the largest installed base of AM machines around the world today, thanks in part to their low cost.

FDM is an iteration of the material extrusion process. One of the advantages of FDM is the durability of the materials used. Other key factors are the stability of FDM parts' mechanical properties over a period of time, and the quality of the parts. The production-grade thermoplastic materials commonly used in FDM are most suitable for creating functional prototypes, as well as making durable manufacturing tools and low-volume manufacturing parts. FDM-made parts are typically found as components in airplanes, as production tools in an automotive factory, or as prototypes in a range of environments.

**Fused deposition modelling**

Ideal for low-volume production of complex end-use parts

Source: Materialise

## Direct metal deposition

Also known as directed energy deposition or laser-engineered net shaping.

Direct metal deposition is one of the most expensive AM technologies. It uses thermal energy to fuse build materials by melting the material as it is being deposited, in a process called directed energy deposition. In most cases, this technique also involves using a laser as an energy source and a metal powder as the build material. It is also possible to melt part of an existing metal object using a laser and then inject metal powder into the pool of molten metal.

**Direct metal deposition**

One of the more expensive 3D printing technologies

Source: Optomec

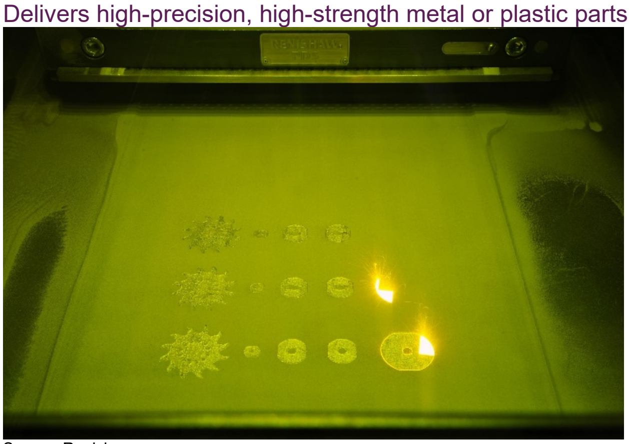
Rather than simply melting powder that sits in a container (known as powder bed fusion), this technique introduces the build material (metal powder) as and when required. This makes it suitable for adding material to an existing part, such as a worn part or tool, which can be restored or modified. By depositing different powdered materials during the construction of a particular part, this 3D printing technique can create complex objects much quicker than traditional manufacturing processes. Direct metal deposition printers produce fully dense metal parts with a strong metallurgical bond to the base material, making them much stronger. Prices for professional systems typically range from $165,000 to well over $1m.

## Powder bed fusion

Also known as selective laser sintering (SLS), direct metal laser sintering (DMLS), selective laser melting (SLM) or electron beam melting (EBM), multi-jet fusion, and direct laser microfusion.

**Powder bed fusion**

Delivers high-precision, high-strength metal or plastic parts



Source: Renishaw

Powder bed fusion is an expensive 3D printing process used to make high-precision, high-strength metal or polymer-based parts. This technology uses a pool of fine metal or polymer powder as its build material. A focused energy source, like a laser or an electron beam, supplies intense heat to specific localized spots and melts or sinters the powder together to form a 3D object. These systems require a powerful source of energy and typically cost upwards of $100,000. Since the patent for SLS ended in 2014, these processes are becoming increasingly common and more financially accessible.

Techniques such as SLS, SLM, EBM and multi jet fusion are all examples of powder bed fusion, which relies on a build platform containing powder material. The process uses a laser or electron beam to melt and sinter particles together at specific points. Once a layer of the object is completed, the platform lowers and more powder is then added. Materials used are nylon (monochrome white thermoplastic powder), stainless steel, titanium, aluminum, and cobalt chrome. One of the key advantages of PDF is its comparatively low cost, but the print process tends to be slow.

## Binder jetting

Also known as inkjet powder printing.

Binder jetting technology falls into the medium price bracket for 3D technologies. Like powder bed fusion, binder jetting uses a powder as the build material but, rather than fusing the powder with heat, binder jetting binds the powder together using a liquid bonding agent (i.e. a kind of glue). However, as no laser is used to sinter the powder, there are no high temperatures involved in the binder jetting process, which means heat-caused disorders are not present. That means bigger parts can be printed because there is less concern that greater cross-sectional area will cause the print to fail. The technology's drawback is the poor mechanical properties of parts. Any plans to make functional parts using binder jetting will typically have to factor in parts post-processing to enhance a part's strength.

The process involves passing an inkjet print head over a bed of powder. The print head selectively deposits glue onto the powder bed and, by working in layers, a three-dimensional object is formed. Build materials can be polymers, metals, or sand. Within this category, further refinements are possible. For example, systems sold by 3D Systems have used plaster-based powders along with a water-based binder and several of the models can print in full color using this technique. ExOne, on the other hand, has developed a technology in which a liquid binder is jetted onto the surface of metal or sand powder beds. When producing metal parts by binder deposition, the printed object is then typically placed in a furnace for sintering and infiltration, which ultimately improves the mechanical properties of the 3D part.

**Binder jetting**

Provides average capabilities for an average price

Source: ExOne

## Material jetting

Also known as multi-jet modelling and drop on demand.

Material jetting also falls into the medium price bracket. Here, droplets of liquid build material are dispensed selectively by inkjet-printing heads as they move across the build area. Materials used in this process include photopolymers (which are hardened by visible light) or wax-like materials (which solidify as they are deposited). The choice of build materials is somewhat limited when using this technique because their properties must enable them to be deposited using a print head. However, the advantage of this technology is its ability to print multi-color and multi-material objects.

The Connex machines from Stratasys, for example, can print parts made of up to 14 different materials. Using this machine, it is also possible to create digital materials, which are composite materials created by simultaneously jetting two different materials together in specific concentrations with the aim of providing particular mechanical and optical properties.

There is a similarity between the way material jetting technology works and two dimensional inkjet printing. Material is jetted onto a build platform, using either a continuous or drop on demand approach. Material is deposited from a nozzle which moves horizontally across the build platform, with the material layers then cured or hardened using ultraviolet light.

The benefits of the process are the high accuracy of deposition of droplets, which reduces waste, and the use of multiple material parts and colors. The drawbacks are that support material is often required for parts and the type of materials are limited, with only polymers and waxes able to be used.

**Material jetting**

Offers high accuracy and low waste, but limited choices of materials

Source: Autodesk

## Vat photopolymerization

Also known as stereolithography and digital light processing.

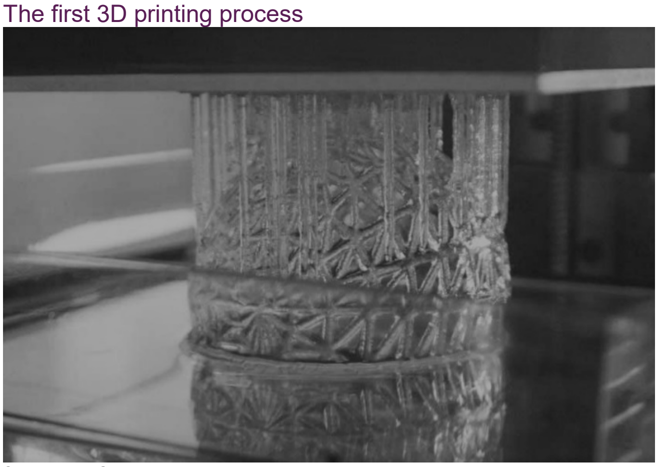
Vat photopolymerization was the original 3D printing technology patented by 3D Systems' Chuck Hull in 1988. This process solidifies layers of ultraviolet light-sensitive liquid polymer using laser technology.

These 3D printers start off with a vat (i.e. a large container) of light-sensitive liquid. The printers selectively harden the liquid by exposing it to a focused beam of radiation, typically ultraviolet light. The resulting 3D object can then be removed from the vat of liquid, ready to use. Objects created using this technique are invariably made of a polymer since this technology specifically exploits the properties of photopolymers, which harden when exposed to light. Parts produced by vat photopolymerization often require support structures and additional post-printing processing, making it a relatively expensive process.

The process typically uses polymers and one of its advantages is a high level of accuracy and good finish. It is also comparatively quick. However, a drawback is that it is also fairly expensive, with long post-processing times and limited access to materials such as photo-resins. The process also requires support structures and post-curing.

**Vat photopolymerization**

The first 3D printing process



Source: AMFG

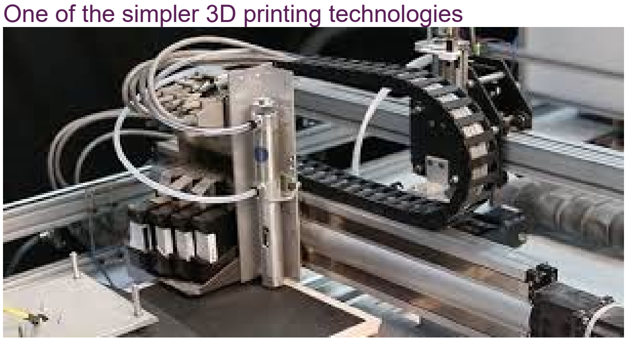
## Sheet lamination

Also known as laminated object manufacturing (LOM) and ultrasonic additive manufacturing.

Sheet lamination is one of the simpler 3D printing technologies. Here the build materials can be sheets of paper, metal tapes, or foil. These sheets are successively bonded together using an adhesive to form a three-dimensional object.

Each layer can be cut into a given profile, using a blade or a laser, and the finished object can be refined further using sanding or curing.

**Sheet lamination**
One of the simpler 3D printing technologies



Source: Autodesk

While this type of process does have its limits, both with regards to material choice and the mechanical properties of the finished objects, the cost of material, in particular for the paper-based systems first introduced by Helisys, is among the lowest in the industry and the systems themselves are also fairly cheap. One of LOM's benefits is its affordability while, for metal LOM, no melting is necessary. A drawback is the low viscosity. There are few mainstream 3D printing companies now regularly working with LOM technology.

## Bioprinting

Bioprinting is the branch of 3D printing dedicated to the creation of living, organic materials, one layer at a time. The build material is a paste of living cells, held in a cartridge. This bio-ink is then deposited in layers on top of each other and interspersed with a gel. The whole operation can take up to an hour or more and must be completed in a clean room, free of contamination.

This process creates a 3D biological structure. Today it is even possible to create living tissue, such as for a lung, a liver, a kidney, or other organ. Bioprinted tissues and organs have been successfully implanted into animals for testing. Recently, advances in printing cartilage tissue have also been made. In future, the aim is to create replacement organs and bone tissue for humans.

**Bioprinting**
Used to print human tissue or create replacement organs

Source: Cellink

3D bioprinted tissues exhibit suitably tissue-like density, with highly organized cellular features, such as intercellular tight junctions and microvascular networks. The ability to create architectural compartments, with different cell types placed in discrete locations relative to each other, results in a microenvironment with cell-to-cell interactions similar to those of native tissues. This, in turn, results in the proper expression and localization of key cellular functions – such as important metabolic enzymes and transporters – over several weeks in culture. The responses of 3D bioprinted tissues to acute or chronic exposure of drugs and known toxins resemble what is observed in vivo – an experiment or procedure done on (or in) a living organism - and in the clinic.

Organovo and EnvisionTEC are the leaders in bioprinting technology. Printers at the top end of the bioprinting market can typically cost from $170,000 to $200,000. Now, however, lower cost 3D bioprinters are available for as little as $10,000.

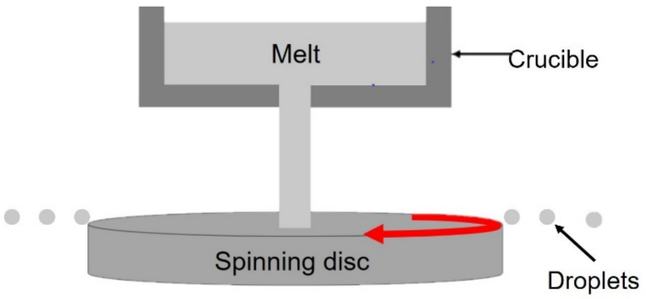
The bioprinting process starts with the identification of key architectural and compositional elements of a target tissue, and the creation of a design that can be utilized by a bioprinter to generate that tissue in the laboratory environment. The next step is to develop the bioprocess protocols required to generate the multi-cellular building blocks – often called bio-ink – from the cells that will be used to build the target tissue. While the bioprinting process is cell-agnostic, most bioprinted tissues utilize primary human cells in order to produce the in vivo-like physiology most relevant for drug testing and for therapeutic applications. It is, however, comparatively early days in bioprinting and, as Organovo has found recently, even though the bioprinting process itself might work, achieving the requisite biological performance from the printed tissues can be challenging.

## The science behind 3D printing

At the heart of the 3D printing process is a computer, Using CAD software, the computer generates a virtual model of the desired object to be printed. In simple terms, the software drives the 3D printer to build the object layer by layer. The printer first melts plastic and applies it onto a stage. This plastic hardens into a layer a few dozen microns thick. Subsequent layers are then deposited on top of previous layers, eventually creating the 3D object. Yet behind this apparent simplicity, science plays a key role in the development of both 3D and 4D technologies, as this next section explains. AM is an economic and sustainable way of producing parts, due to the negligible amount of waste produced. Leftover build materials can be recycled and parts produced by 3D printing can be used in the 3D printer. In this way, it is a circular economy. Powder particles can either be produced by mechanical, chemical, or atomization processes. Mechanical milling produces homogenous and fine powder, if processed for long periods of time.

**Producing the starting materials**

Centrifugal atomization




Source: GlobalData

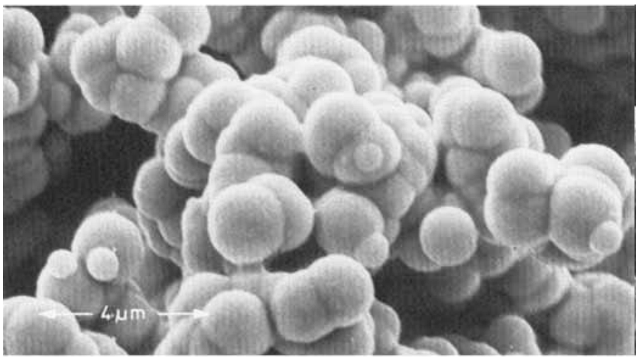
Atomization is a way of producing metal powder from metal melt. Centrifugal atomization produces powder when metal melt hits a rapidly spinning plate. Twin fluid atomization uses high pressure fluid to break up a narrow stream of metal melt into powders. The original AM process begins with a liquid photosensitive polymer that solidifies when subjected to a UV beam. UV radiation causes polymerization by producing radicals that react to form a cross-linked solid polymer. Only photosensitive materials can be used. In some cases, the mechanical properties of some polymers will prohibit them from being used in engineering applications.

### The properties of raw materials and how this affects processing

The properties of the powder affect the ease and success of 3D printing. Spherical particles pack most efficiently, improving the mechanical properties and surface finish of AM parts. In addition, having a range of particle sizes increases this packing efficiency. Smaller powder particles are able to fit into the gaps between larger particles, therefore decreasing porosity. A fine and rough powder, however, has poor flowability. This leads to powder agglomerations and poor compaction, producing a heterogeneous microstructure and anisotropic properties

**Smooth powder’s better molecular structure improves flowability and printing**

Poor compaction of powder is caused by poor flowability and powder agglomerations




**Smooth powder**


**Rough powder**

Source: Johnson Matthey

### Flowability

Flowability is the measure of a particle's ability to flow. Particle size, geometry, and surface roughness all affect its flowability. Many 3D printing processes begin with a powder bed in which the powder must have good flowability so that it can pack densely into the tray, without the need for extra compaction stages. 3D printed materials need further processing to optimize mechanical properties, including fatigue life, as well as tensile and flexural moduli. Post-printing treatments include surface polishing, sintering, and hot isostatic pressing (HIP).

HIP is a process that increases the density of a material by holding it in high temperature and pressure gas. A component that has undergone HIP can reach 100% of its theoretical density, reducing the porosity, which improves fatigue life.

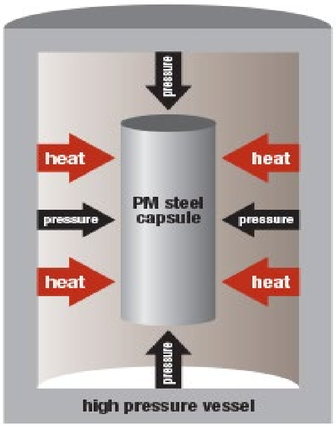
Surface polishing can also improve fatigue properties, as the number of flaws on the surface, which can initiate fracture, decreases. However, this is not always the case, and depends on the material used, further illustrating the complexity of 3D printing.

Sintering is another post-printing process that is often used to increase mechanical properties.

**Post 3D printing processes**

Hot isostatic pressing, surface polishing and sintering are all used to enhance mechanical properties

HIP




Source: GlobalData, Deloro

### Sintering

During this process, atoms rearrange themselves when the part is heated, thus filling voids and increasing the part density. Sintering improves mechanical properties such as fatigue life and failure stress, meaning that the part will last longer under a cyclic load and can withstand higher loads. The shrinkage during sintering will vary based on the sintering conditions (typically time, temperature, pressure), materials' properties (particle size and shape), and amount of porosity. By controlling the amount of porosity, it is possible to reduce the amount of shrinkage and improve dimensional tolerance. Shrinkage should be accounted for in the design stage and can be predicted via various numerical models, such as the SOVS model, which is one of a number of approaches that set out to understand and predict sintering behavior.

### Properties of 3D printed parts

3D printing produces parts with different mechanical properties to those produced by traditional methods. The exact variation in properties varies depending on the material used, powder contamination, printing geometry and rate, and post-printing treatments. Further difficulty arises when inconsistent properties are exhibited by different batches of AM parts. Although the external appearance is identical, the mechanical properties exhibited between different batches can be quite marked and more research into this area is required. Whilst post-printing treatments can improve the mechanical properties of the part, they add time and cost to the process, which detracts from the unique selling point of 3D printing.

## The technology of materials

The anticipated strong growth in the 3D printing marketplace has encouraged the development of an array of materials for 3D printing, spurred by the support of a number of chemicals companies. Key players include BASF, GKN, Henkel, Materialise, Solvay, Sandvik, and Höganäs.

The entry into the 3D printing market of big players such as HP and GE Additive, organizations that are betting their business on achieving rapid success in this nascent market, has itself demonstrated to the chemicals companies that 3D printing is a strong area for investment.

The 3D printing industry's growing maturity and sophistication is also arguably a factor. The industry, now in its mid-thirties, is seeing a new application-driven move towards innovation which is matching relevant applications with the requisite materials. Consequently, material manufacturers are keen to develop new materials to suit those applications. Materialise, for example, introduced two new plastic materials: polypropylene (PP) for laser sintering, and Taurus, a stereolithography material.

BASF, meanwhile, has introduced specific powders for the powder bed fusion process, in which thin layers of powder particles are locally fused, e.g. by a laser, and built up layer by layer into the desired shape. BASF claims its Ultrasint powders enable greater stiffness, strength, and toughness, as well as higher heat deflection temperature. Fillers are embedded into the polymer particles, thus ensuring easy handling and more isotropic part properties.

BASF claims that these powders have several potential uses. The need for lightweight designs and resiliency in the metal plating process offers possible applications such as wing shapes, lattice structures, antennas, and galvanization. The need for temperature resistance and toughness then drives possible applications such as the creation of engine covers, manifolds, heat shields, oil pan covers, air ducts, brake ducts, connectors, and brackets. The desire to have high burst resistance at temperature creates potential applications such as oil separators, air intake systems, environmental control ducting, plenums, housing for (brake) fluids, fuel filling pipelines, or fuel valves. Finally, the need for flame retardant applications provides user cases such as customized cabin components, connectors and switches, terminal strips, circuit breakers, and easy metal plating.

This bespoke approach is critical for technical industries such as aerospace and automotive that, not least for safety reasons, need materials with specific properties and quality requirements. In the past, such industries would have had to balance the design benefits and competitive advantage they get from AM against any potential downsides in cost or performance. The difference now is that the new materials change the landscape. Industries will be able to choose the materials that best serve their applications, whether they are for functional prototypes or for series manufacturing.

While the rise in manufacturing applications, as opposed to prototyping ones, is fueling a growth in materials development, it also bringing with it new challenges, such as the need for materials standardization and better machine control, especially for industries with highly demanding quality requirements, such as aerospace and medical devices.

Any difficulties encountered with materials will create a drive to find an alternative. For example, acrylonitrile butadiene styrene (ABS) was among the earliest of materials used in FDM 3D printing. It is one of the most commonly used plastics, used in processes such as injection molding and the creation of airplane seats and Lego bricks. However, ABS is renowned for being tricky to print with and so polylactic acid (PLA), a thermoplastic polymer, replaced it as a material for general usage.

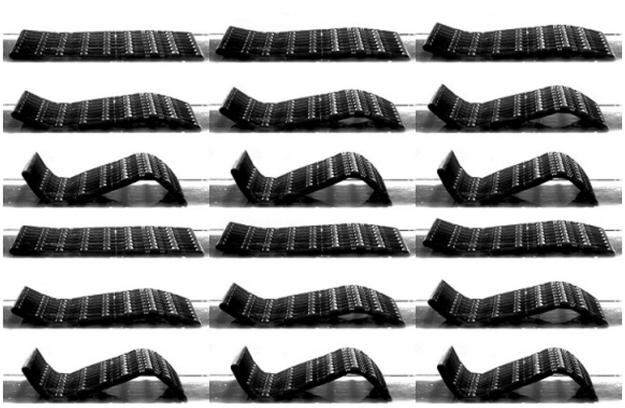
For now, polymers – particularly plastics – account for a greater share of the materials marketplace than metals. However, the growth in metals usage is likely to drive a change that could see metals outstripping polymers, possibly by the end of 2021.

## 4D printing

The march of technology is such that, having achieved 3D printing, there is naturally a desire to go one dimension further. In 4D printing, a 3D printed part transforms itself in response to an external stimulus (e.g. time, heat, moisture, sound) and becomes a smart material. There are applications in construction, wearable tech, and autonomous vehicles, among many others. In future, the aim is to produce buildings that can react to weather conditions, prosthetic limbs with built-in sensitivity, and even self-assembling flat pack furniture. Smart materials are a relatively new idea, with the term first being coined in 2013. The technology is still confined to labs and it is predicted that it will be another 10 years before we begin to see 4D printed smart materials in our lives.

**A 4D printed object can change its shape and behavior**

Functionality can be impacted by water, light, and heat



Source: GlobalData

Skylar Tibbits, founder of the Self-Assembly Lab at MIT, told GlobalData that 4D printing offers us something that 3D printing cannot: “Whilst 3D printing is an alternative way of producing the same products, 4D printing can make products that can’t be made by other methods. We are able to print non-static, highly intelligent, active parts that sense and self-transform, without adding heavy and expensive sensors or motors. Smart materials traditionally form a niche category that have fixed properties and are difficult to implement. With 4D printing, we are better able to customize products by programming sensing and actuating ability into the material itself, giving us functionality that we were unable to access before,” he explains.

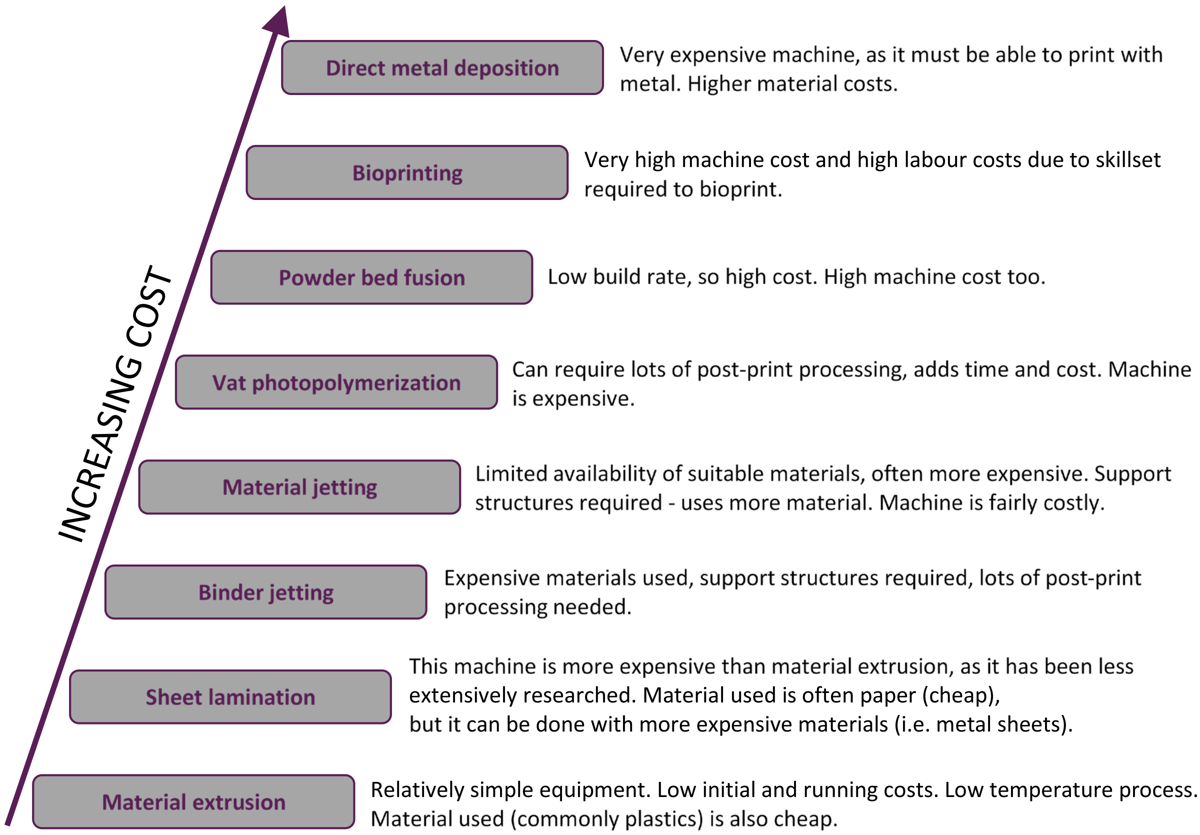
Tibbits foresees smart materials becoming ubiquitous, from producing cars that adapt to local conditions to shoes that shape to our feet. Despite these brilliant use cases, scalability may prove to be complex. Whilst the Self-Assembly Lab has produced a number of prototypes that demonstrate sensing and transformation, no one has yet replicated this on a large scale. There are also likely to be issues in satisfying repeatability tests and regulations, as there is currently no standard method or software for printing smart materials. However, Tibbits is confident there are no fundamental hurdles which will stunt the growth of this revolutionary field.

## The cost of 3D printing

The cost of 3D printing ranges from the lower costs of materials extrusion to the very expensive costs of direct metal deposition. The choice of process largely depends on the end goal, the required quality of the finished product, the duration of the process, and the overall cost picture.

**Ranking the cost of additive manufacturing methods**

Direct metal deposition and bioprinting come out most expensive




Source: GlobalData

# Trends

The main trends in the 3D printing industry over the next 12 to 24 months are shown below. We classify these trends into three categories: technology trends, macroeconomic trends, and regulatory trends.

## Technology trends

The table below highlights the key technology trends impacting the 3D printing industry.

| Trend | What's happening? |
|---|---|
| **From prototyping to digital manufacturing** | The mindset around 3D printing is shifting and there is an aspiration to change the terminology to move beyond prototyping and think in terms of bigger volumes. The disruption in value chain means wider thinking, more in terms of digital manufacturing than 3D printing. Also, the wider idea of digitally manufacturing parts – say, for the automotive marketplace – offers potentially much greater commercial success. |
| **Sustainability** | The global focus on climate change and global warming is driving a greater sustainability focus, based on the idea of creating a circular economy around 3D printing, instead of a linear one (where the mindset is typically one of 'take; make; and dispose'). It means keeping materials in use for the longest period of time at their highest available value. By utilizing changes in design – and cutting out unnecessary parts – the weight of parts created can be reduced by over 93% in some cases, meaning a reduction in carbon footprint of up to 95%. |
| **Materials** | The entry of several chemical companies into the 3D printing market is helping drive the use of new innovative materials and compounds. Those companies include BASF, which is supplying its Ultracur3D ST 45 urethane resin to Paxis and its Ultrasint PA6 (polyamide 6) powder to startup Impossible Objects. Other materials currently in use include glass fiber and diamond-based polymer composites, not to mention plastic powders, plastic filaments, photopolymers, hydrogel, metals, ceramics, and biomaterials, including hydrogel tissue-derived bio-ink, and synthetic and biodegradable polymers. Early in 2019, T&R Biofab registered a patent for its 3D bioprinting technology to create artificial skin. The technology operates through the 3D printing of dermal (inner skin layers) and epidermal (outer skin layers) cells that uses a porous 3D structure to form skin with similar characteristics to actual human tissue. |
| **Digital twins** | Digital twins is a concept from the Industrial Internet that is now being adopted for 3D printing. NASA first used the idea of digital representations of physical objects for its space projects. It was not able to see and monitor systems physically because they were too far away, so it created digital models to simulate and analyze the systems back on Earth. In the Industrial Internet, a digital twin provides a holistic view of the capabilities of an asset and so can help orchestrate, manipulate, or program certain aspects of an Industrial Internet device. In 3D printing, digital twins' advanced analytics enable organizations to be able to close the loop between a digital production plan and its actual performance. Siemens' MindSphere software interrogates an Industrial Internet data pool to feed insights back into the digital twin of a multi jet fusion process, thus enabling an organization to troubleshoot what happens before and after printing with equipment, material flow, and worker performance. That means being able to better optimize processes for future projects and provide feedback into design and engineering. |
| **Design benefits** | One of the benefits of 3D printing is the greater design freedom it enables, with a continual iterative process reducing components, weight, and, ultimately, manufacturing cost. While previously designs developed for conventional manufacturing were hampered by manufacturing processes that required the creation of separate components assembled to create the end product, 3D printing has the potential to remove many of the constraints of the traditional manufacturing process. With 3D printing, there is also no additional cost to creating a complex design. Unshackled from traditional manufacturing constraints, designers will be freer to create geometries that better achieve their desired performance and meet customer needs. GE took advantage of this freedom to redesign the LEAP jet engine nozzle from 18 separate components to a single part. That decreased the product's weight and increased its performance with complex internal pathways. |

| Trend | What's happening? |
|---|---|
| **The appliance of science** | The science around 3D printing, particularly metal, is still developing. At the same time, the process of 3D printing is opening up new possibilities in other scientific areas. A recently 3D printed model of a lung-mimicking air sac was created, complete with functioning airways capable of delivering oxygen to surrounding blood vessels. It was made by a team of researchers in the US by gradually building up layers of hydrogel, a synthetic, jelly-like material that shares many features in common with human tissue. The same approach could be used to create complex vascular networks that mimic the body's natural passageways for blood and other vital fluids, thus opening up the possibility of creating a new means of bioprinting human organs for transplant. Work is now underway in the US involving several universities, including Rice University, and Massachusetts design firm Nervous System. Previously, one of the biggest barriers to generating functional tissue replacements was an inability to print the complex vasculature that can supply nutrients to densely populated human tissues. |
| **Partnerships** | The need to better understand the industrial automation and materials world is driving more partnerships. HP, for example, is keen to learn from Siemens' industrial automation expertise, and BASF's 3D printing materials specialism. It is also working closely with GKN in the same materials arena. Other alliances include Stratasys with Solvay, BASF with Impossible Objects, and French chemicals company Arkema with Carbon. |
| **Specialist applications** | Some argue that the future for the industry is not so much in technology but in applications and that is what will attract and keep the attention of investors. Materialise's chief executive Fried Vancraen has suggested that investments are not going to machine manufacturers anymore but to companies and start-ups that apply 3D printing technology to create added value in specific domains. He believes creation and stimulation of user demand is what will accelerate 3D printing further. Asia is a fast-growing market for 3D printing and governments that might previously have invested in 3D machine manufacturing are now looking instead to stimulate 3D printing consultancy and co-creation. Materialise is helping manufacturing companies in Ulsan in South Korea to develop applications through co-creation projects combining Materialise's 3D printing expertise with the manufacturing companies' knowledge of their industry, market and product. Meanwhile, the German multinational Thyssenkrupp has argued that the 3D printing industry could generate an incremental value of $100bn by 2025 for the Association of Southeast Asian Nations (ASEAN). |
| **More materials** | Although there is a strong move towards greater adoption of metal 3D printing, materials manufacturers, including an increasing number of chemicals companies, are starting to produce a variety of new powders, including polymers. That, in part, will also be driven by the expected rise in manufacturing applications, rather than prototyping ones. |
| **Automation and software** | As organizations start to integrate 3D printing into their production options, they come up against the twin issues of reducing cost and increasing efficiency. In short, there is a need to improve productivity, which means greater automation of tasks. Software will be key in achieving this. Incorporating simulation into 3D printing workflow can help reduce cost elements such as consumables and machine time. Simulating the 3D print process can make it easier for production operators to spot potential errors before a build starts. |
| **Interoperable, not proprietary** | This mirrors one of the continual arguments within the IT industry: the need for greater interoperability and technology-neutral solutions rather than proprietary ones. There is an ongoing argument that if the 3D printing industry is serious about getting industrial manufacturers to consider 3D printing as a valid manufacturing technology for final products, then tying industry's hands by locking them into proprietary solutions that limit flexibility and choice may not be the best way to go. |

Source: GlobalData

## Regulatory trends

The table below highlights the key regulatory trends impacting the 3D printing industry.

| Trend | What's happening? |
|---|---|
| **Global standards** | For an industry to develop a strong market, the need for standardized processes is critically important. Standardization covers best practices, regulations, and benchmarks that guide industries and organizations. 3D printing is an emerging, disruptive technology in which standards are expected to provide a much-needed foundation to facilitate wider adoption of the technology, beyond prototyping and into wider digital manufacturing. As the market grows, the areas of better quality assurance and process consistency will be key. There are two core benefits of standardization for 3D printing: ensuring consistency; and meeting regulatory standards. On consistency, the need to continually be able to produce parts of high quality and guarantee a repeatable process each time remains one of this fledgling industry's biggest challenges.<br><br>3D printing consists of a complex network of variables, from raw materials to design optimization and manufacturing processes, which in turn require interaction between an infrastructure of software and hardware. Each of these stages must be monitored, assessed, and controlled to ensure the repeatability and reliability of 3D printed parts, whilst avoiding a costly trial and error approach. Adopting a standardized approach can help to define the parameters for each step of AM production, while creating a consistent process every step of the way.<br><br>In terms of regulatory standards, notably in highly regulated industries such as medical, automotive, aerospace, and defense, issues with product certification risk delaying wider 3D printing adoption. Parts produced with additive technologies have properties that can be quite different from those achieved with subtractive manufacturing, leading to complications around quality assurance and certification. Areas where standardization for 3D printing is needed include materials, process control, and certification. |
| **Medical devices** | In December 2017, the US Food and Drug Administration (FDA) published guidance to manufacturers of 3D printed medical devices in response to 3D printing's growing adoption by the healthcare industry. The FDA's guidance offered manufacturers of 3D printed medical devices a path to regulatory compliance, though it probably won't be the last piece of advice issued. A Stratasys blog on the subject suggested that the FDA will expect to review some manufacturing information, such as the orientation of a printed object and the printing location. The FDA has also suggested that manufacturers should submit a production flow diagram and a high-level summary of each critical manufacturing process step. Its rationale for this is that "the effects of the different steps in the [AM] processes can be seen in final device testing. However, determining the root cause of failures from manufacturing defects can be very difficult without a clear understanding of each step." |
| **Copyright and piracy** | A paper published late in 2018 entitled "From IP Goals to 3D Holes: Does Intellectual Property Law Provide a Map or Gap in the Era of 3D Printing?" discussed the issues around intellectual property law and 3D printing. It suggested 3D printing is complicated as it "stretches across many facets of the law." It involves a machine, a product, a digital process, and often the translation of that process. The author, Autumn Smith, suggested that: "Much like the Internet, 3D printers separate the content of the product from the information used to create it, which, in turn, will substantially reduce the manufacturing costs. This feature will inevitably mean that the production of items can come from virtually anywhere, which will certainly present problems for governments and markets."<br><br>Another issue is the sheer diversity of things that can be printed, including weapons, leading to uncertainty and, in some cases, heated debate, about the laws surrounding them. In June 2019, a UK man was convicted of making a 3D printed gun that was capable of firing a deadly shot, while a battle has raged in the US over whether 3D printed guns are legal or not (see the entry for traceability below). |

| Trend | What's happening? |
| --- | --- |
| **Objects versus digital files** | In 2016, the UK government was urged in a report by Innovate UK to develop a national strategy for AM and create a network of users and developers. The report also called for a widening of initiatives on skills and education. To date, it has been difficult for governments to understand what they can empower, in terms of 3D printing, through policymaking. Two key areas are intellectual property and product liability. There remains a concern that the possibilities offered by 3D printing could replicate for physical objects what the internet has done for music and films, i.e. rip up business models and shift the value from the physical product to the digital file. There is a risk that governments overestimate how much value is on the digital file as opposed to the physical object, meaning there remains a need to consider how digital files are regulated. |
| **Traceability** | The legal minefield around 3D printing is exemplified by a case brought by the US government against an individual who 3D printed a handgun. Cody Wilson developed the pistol almost entirely of plastic, calling it 'The Liberator'. He posted the printing manual online, from where it was downloaded nearly 100,000 times. The US government subsequently ordered Wilson to remove the files and, though he complied, he then contested the order in court, and years of litigation followed. In June 2018, the case was finally settled with Wilson winning the case. The concern from US regulators on 3D printed guns is over traceability and detectability, as 3D printed guns lack the serial numbers that register mass-produced guns with the federal government, and they cannot easily be traced. As they are made of plastic, they can also slip through metal detectors. In August 2018, a day after a federal judge extended a temporary block preventing Wilson from making the 3D printing plans available on the web for free, Wilson said he'd start selling the blueprints that would allow users to 3D print their own plastic guns. The issue around using 3D printing to make guns has now spread to the UK after a student became the first person in the UK to be convicted for using a 3D printer to manufacture a gun. |

Source: GlobalData

## Macroeconomic trends

The table below highlights the key macroeconomic trends impacting the 3D printing industry.

| Trend | What's happening? |
|---|---|
| **Educating the engineers** | For the 3D printing market to grow, executives in the industry talk of a need to educate both current and future engineers of what 3D printing can do for them. Instead of automatically considering an injection molding solution, could a 3D printing solution work instead? Some 3D printing suppliers are keen to accelerate the awareness and understanding of the potential of 3D printing by encouraging the creation of university courses. They argue that, if you can't influence the present generation of engineers quickly enough (or if they're too resistant to change), then at least you can get the possibilities of 3D printing into the heads of the next generation. GE Additive has announced an Additive Education Program (AEP) that aims to give over a million students the opportunity to use 3D printing by 2020. The company expects that a total of 2,001 schools and 1,296,500 students will have been reached since the program's launch in 2017. |
| **M&A** | There have been several examples in other industries, particularly the computer industry, where companies have been acquired for the talent of their people. The term coined for this is 'acqui-hiring' and it is now happening in the 3D printing industry. In 2019, EOS acquired the Texas-based powder bed fusion R&D startup Vulcan Labs. Vulcan Labs began as a spinoff of Stratasys, one of EOS's major competitors, and was established as a research and innovation entity in order to develop its technology for metal manufacturing. Several of the people who had joined Vulcan Labs were themselves part of a 3D printing service bureau, Harvest Technologies, which Stratasys acquired in 2014. EOS described the Vulcan acquisition as like having struck the AM talent jackpot. |
| **Legal battles over intellectual property** | The business opportunity vendors now see from the 3D printing industry is visible in the legal battle continuing between two competing metal 3D printing providers. Desktop Metal and Markforged have had a skirmish before, with Desktop Metal alleging Markforged had infringed its proprietary metal 3D printing technology. The companies came to an out of court agreement after Markforged alleged that Desktop Metal employed "dirty tricks" against Markforged and acted like "schoolyard bullies" in the dissemination of false information about Markforged's metal 3D printer and associated products. Generally, the 3D industry has benefited from healthy but friendly competition. The legal battles suggest a maturing industry, with vendors prepared to act legally to defend what they see as their competitive position. |

Source: GlobalData

# Industry analysis

The 3D printing industry is on an upwards curve, with confidence greater than perhaps at any time in its history. The technology is tried and tested, though in metal 3D printing there is more to do, and large manufacturers are embracing the possibilities (e.g. Airbus recently sealed a deal for Ultimaker to supply it with 3D printers, software, and materials for its European facilities.)

Investment money is also finding its way into 3D printing start-ups. Desktop Metal, a Massachusetts-based metal 3D printing technology company, closed a $160m Series E funding round led by Koch Disruptive Technologies (KDT) in 2019, taking the total raised since its foundation in 2015 to $438m in combined funding. One of its backers includes Ford, whose chief technology officer, Ken Washington, now sits on Desktop Metal's board, as does former GE chairman and chief executive Jeffrey Immelt.

Originally 3D printing's default use-case was regarded as prototyping, where prototypes were used as a way to test designs. Prototyping is still the primary application but 3D printing is now making larger steps, if not quite yet giant strides, towards serious manufacturing. Driven mainly by the automotive and aerospace industries, engineers are now examining how to integrate additive into their manufacturing portfolio.

Prototyping remains the primary step before any wider move into manufacturing is possible. Ultimately, 3D printing can only be a part – albeit a significant part - of the overall solution. It will not replace traditional manufacturing technologies, such as CNC machining (in which pre-programmed computer software dictates the movement of factory tools and machinery) or injection molding (in which parts are produced by injecting molten material into a mold). However, it will work alongside them to create a digital manufacturing ecosystem. 3D printing is also increasingly being used for maintenance and repair of damaged parts, particularly for products with long lead times.

That said, currently 3D printing accounts for just a fraction – less than 0.1% - of the overall global manufacturing market, which is currently valued at $12.7tn. GlobalData believes the 3D printing market will be worth $32bn by 2025 and over $60bn by 2030.

## There are five clear use cases for 3D printing…

3D printing tends to be best utilized for small production runs where customized products and short development cycles are the norm. Previously 3D printing might have been best suited for smaller products because there were limits to the size of affordable 3D printers, but that is changing. 3D printing is certainly suited to goods of high complexity because the creation of complex geometric features is difficult to achieve with more traditional machining methods but is relatively easy with 3D printing.

There are five key use cases for 3D printing.

- **Rapid prototyping.** In many engineering and design organizations, rapid prototyping and proof of concept is the first step towards getting the go-ahead for wider production. According to a 2019 report by Sculpteo, 80% of high tech manufacturing respondents are relying on 3D printing for prototyping.
- **Accelerating product development.** According to the same Sculpteo report, 3D printers are also being used to accelerate product development. Mass customization and support for configure-to-order and engineer-to-order product strategies are also a high priority. The Sculpteo survey found that adopting a design-to-manufacturing strategy accelerates new product development and innovation. When asked which elements of 3D printing they spend most time on, nearly 50% of respondents said CAD design. Nearly 70% of enterprises found new applications for printing in 2018 and 2019, with 60% using CAD, simulation, and reverse engineering internally.
- **Increasing production flexibility.** This is another area that is driving manufacturing strategies, making 3D printing part of the manufacturing mix alongside CNC machining and injection molding.
- **Tooling.** 3D printers can be used to make tools, often using 3D scanners. The scan-modify-build process facilitated by 3D printing technology can produce savings on tooling costs. Now, instead of re-creating molds from scratch, manufacturers can scan an existing one, analyze the wear and tear, design an improved model, and make new molds in days rather than weeks. They can also do it all onsite.
- **Maintenance and repair.** The ability to repair metal parts to become near-new shapes has significant advantage over manufacturing new parts, particularly large parts where only a small portion of the part has been damaged. Corrosion and wear costs the US economy $300bn per year, while the global commercial aviation industry spends almost $100bn annually on repair. 3D printers are increasingly being used for maintenance and repair of damaged parts, particularly for products with long lead times.

## …and increasingly, 3D printing will be used in digital manufacturing

Some vendors are beginning to use the term digital manufacturing to describe the shift from 3D printing to a bigger function. 3D printing is now becoming part of the manufacturing mix to be considered alongside CNC machining and injection molding, though it will not replace them.

The three approaches are defined like this:

- **3D printing.** The process of building a 3D object from a CAD model, usually constructing the part by depositing layer upon layer of material i.e. additive manufacturing. Professionals use 3D printing for two purposes: as a prototyping solution to accelerate product development or as a manufacturing technology for the production of end use parts. The benefits of 3D printing for prototyping are the ability to have rapid design iterations, low-cost, functional prototypes, and effective design communication. For wider AM, the benefits are fewer design restrictions and on-demand production.
- **CNC machining.** The process of taking a blank piece of material and, following a precise set of programmed instructions, to remove material from the block until only the final product remains. In terms of picking the right process, when the need is for low volume of parts, CNC machining is the quickest process. If 10 parts are needed in two weeks, CNC machining is probably the solution. If the target is 50,000 parts in four months, injection molding is the better way to go.
- **Injection molding.** The process of heating resin and injecting it at pressure into a mold cavity, which then solidifies and sets, before being ejected. Injection molding requires time to make the mold and ensure the parts are in tolerance. This can take anywhere from a few weeks to a few months. Once this is done, creating parts using the mold is a very fast process. The upfront time investment of injection molding pays off at high volumes.

## Market size and growth forecasts

The 3D printing market is set to follow a steep growth curve for the next few years. The market, which accounted for just over $11bn in spend in 2018 (when sales of 3D printing hardware, software, materials and services are included) is set to be over $13bn by the end of 2019, rising to $32bn by 2025, and over $60bn by 2030.

The market breaks down into hardware, software, materials, and services.

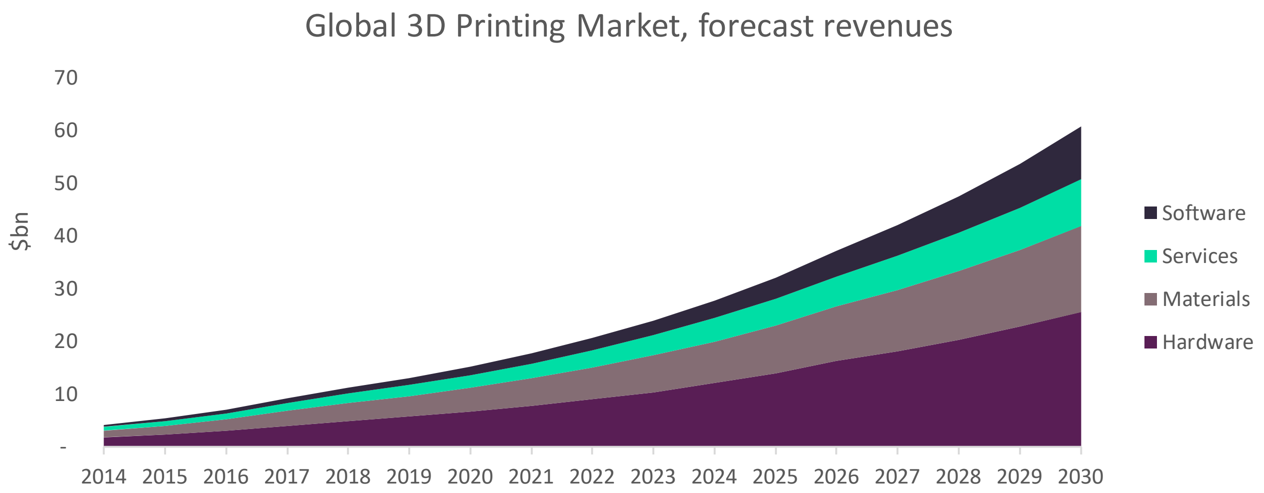
- **Hardware:** Refers to the machines that actually do the work of the additive processes to make physical things.
- **Software:** Refers to the programs that convert design data into fabrication data, as well as the software onboard the machines and the software that routes data to the machines. This includes CAD software, slicing software and programs designed to track the flow of the 3D printing process, such as digital twins.
- **Materials:** Refers to the printing supplies of specialized polymers, ceramics, and metal alloys, supplied in powder form, which are the building bricks of 3D printing, as well as any consumables required for specific processes
- **Services:** Includes a range of consulting services, comprising design and both production and factory management. It also includes repair services.

Our forecast assumes steady compound annual growth of around 16% in hardware, materials, and services and around 20% in software from 2018 to 2025, when growth rates will start to flatten. By 2030, when the 3D printing industry will have matured, growth rates on hardware, materials and services will fall to around 12% when 3D printing revenues will exceed $60bn. Software growth rates will remain high at around 20%.

However, all market predictions are dependent on the state of the global economy, and the impact of the trade war in 2019 between the US and China may impact growth rates. Growth is also dependent on the implementation of successful corporate strategies, and 2019 results from several vendors have suggested that while strong 3D printing growth is likely, it is not necessarily a given.

**By 2030, the global additive manufacturing market will exceed $60bn in spend**

Hardware and materials revenues will comfortably outstrip those from services and software




Source: GlobalData

### By the end of 2021, metals will overtake polymers

The moves of companies such as HP and GE into 3D metals printing has given more momentum to the metals market. According to Deloitte, between 2017 and 2018 metal printing's share of the market rose from 28% to 36%. While it is possible that metal will represent half of all 3D printing by 2020 or 2021, it is more likely that any metals-polymers crossover date, if it arrives, will take a while longer. New premium polymers such as polyetheretherketone (PEEK) and polyetherketoneketone (PEKK) are being developed as alternative material, for example, to titanium. Another area that is attracting interest is carbon fiber printing.

2018 was a strong year for the global 3D printer market, with growth led by the industrial printer segment, which accounts for around 70% of global 3D printer revenues. Some estimates have put the overall share of the industrial and professional segments together at 81%. Growth was largely due to the availability of new, lower-priced metal and polymer printers from companies such as Markforged, Desktop Metal, HP, Carbon, and 3D Systems.

2019 is likely to see continued strong growth in machine shipments of 25%, with metal printer shipments likely to rise by well over 40%, and polymer machine shipments growing by over 20%.

As costs have fallen, the type of printer that a company can afford to purchase has changed. The typical cost of printers is now between $100,000 and $125,000, compared to the average price of a similar printer in 2017 of approaching $500,000. Industrial machines can be defined as those costing over $100,000, with design machines costing between $20,000 and $100,000. Professional systems have been defined as those costing between $2500 and $20,000.

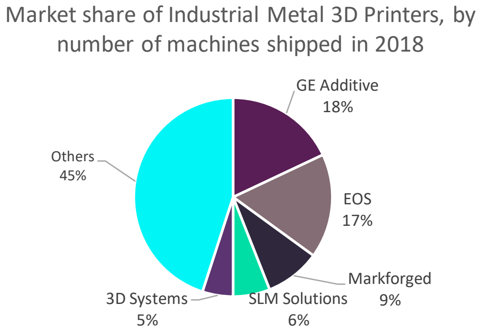
## Competitive analysis

The industrial printing market has been led for some years by Stratasys and 3D Systems, with the growth in metal printing seeing EOS, and now GE Additive, start to take market share. The market has become even more competitive, not only because of HP's recent entry but also because of the rise of companies such as Markforged and Desktop Metal in the metals space and by Carbon in the polymer sector. HP expects to provide serious competition in metal 3D printing, but it is likely to be at least two years before it has developed a market offering. It is making a big bet on the growth of the company through 3D printing and digital manufacturing.

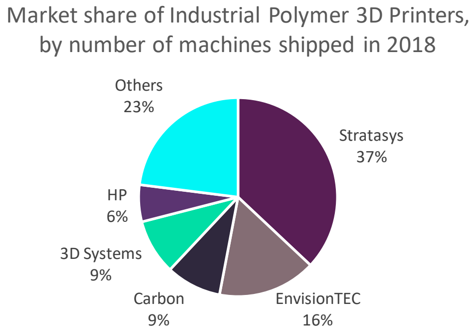
SLM Solutions had a poor first quarter to 2019, with the number of ordered machines down a third on those ordered in the same period of 2018, and half year revenues 44% down. Some of its share of the market is now at risk of being eaten away by a combination of EOS, GE Additive, Markforged and 3D Systems.

**New blood starts to make its mark on the 3D printing market**

GE Additive and Markforged do well in metals




Carbon makes progress in polymers




Source: GlobalData, Context

GE Additive has previously said it hopes to deliver revenues of $1bn by 2020, but has failed to explain how it intends to go about achieving it. Its parent General Electric's wider misfortunes do not inspire confidence that it will hit its targets. However, GE Additive did win a four-year, $9m deal from the Office of Naval Research to develop a process for creating 1:1 scale twin digital models of metal 3D printed parts for the US Navy. The company is also selling internally. GE Aviation recently bought 17 Arcam A2X systems and 10 Spectra H systems from GE Additive.

Desktop Metal is a 3D printing unicorn, one of a number of new players with big ambitions in the 3D metal printer space. Although the current market for 3D metal printing is smaller than the one for print polymers, it is regarded as being on an upward curve. Desktop Metal is said to have racked up a backlog of orders worth $120m in 2018, putting it on target to reach revenue of $100m in 2019. An initial public offering (IPO) is on the horizon.

Even the accepted leaders in their field can face setbacks. Organovo, for example, has been strongly associated with the development of bioprinting but, in August 2019, it hired a financial advisor to assist in the exploration of strategic alternatives after admitting that it had failed to generate decisive scientific data supporting the prolonged functionality and therapeutic benefit of its lead liver tissue candidate.

### Where is the desktop systems market headed?

Although the market for industrial systems is thriving, the future of the desktop systems market is unclear. A 2018 prediction that desktop 3D printing was in decline was a surprise to several vendors, which argued that the market is still set for significant growth as there is a large amount of people who are unaware of 3D printing and who could be potential buyers. However, the 2019 Wohlers Report also suggested that desktop 3D printing systems saw a decline in annual growth.

It has been suggested that, although there is a clear industrial 3D printing market, there is a lack of a true consumer market. There is a hobbyist market – which is a target market for desktop 3D printers – but there is a difference in scale between consumer and hobbyist markets. Consumer devices are expected to be plug and play, with sales measured in terms of millions of units, while a hobbyist market would probably be measured in tens or possibly even hundreds of thousands of products.

In the desktop systems marketplace, the market leader in personal (retail price of under $2,500) systems is XYZprinting. Ultimaker and Formlabs lead the professional class (priced at between $2,500 and $20,000) in terms of market share.

There is an argument that the sub-$2,500 market, which previously comprised vendors such as MakerBot, Tiertime, XYZprinting, and Ultimaker, has shifted, with those vendors moving up and the price moving down to sub-£1,000. Ultimaker has big ambitions, having been selected by aircraft manufacturer Airbus to supply its 3D printers, Cura software, and materials for use in Airbus's European facilities.

Stratasys-owned MakerBot is also a key player in the desktop 3D printing world and is utilizing its parent's industrial capabilities. The MakerBot Method X manufacturing workstation will use the Stratasys connection to solve the issues that desktop 3D printers have struggled with, notably the cracking and warping of parts, using some materials. Method X is designed to reduce shrinkage rates and produce parts that are more durable.

Other challengers in the personal and desktop area are Aleph Objects, Zortrax, Leapfrog, Creality, Prusa Research, and Sinterit.

## The new kid on the block is 4D printing

3D printing, together with increasingly complex materials, is leading to the concept of 4D printing, a development that will open doors for new product innovation possibilities. 4D printing takes 3D printing a step further to enable the creation of three-dimensional objects that incorporate a fourth dimension: time. The development has the potential to redefine how we design, manufacture, and interact with objects by using smart materials to create objects that can self-assemble, reshape themselves, or otherwise react to changing conditions.

Many of the industry-leading 3D printing companies, such as HP, Stratasys, and 3D Systems, have also invested in 4D printing (GE Additive though has not yet invested in this area).

One of the leading organizations in the 4D printing market is MIT's Self Assembly Lab, in collaboration with Stratasys and Autodesk. Some market commentators estimate that the 4D printing market will be worth over $360m by 2025.

However, as in 3D printing, stringent regulations in sectors such as healthcare and aerospace can stymie the progress of scientific development in a bid to protect users from harm or unintended side effects. Given these challenges, commercialization is at least 10 years away.

## Mergers and acquisitions

The most notable 3D printing M&A deals of the last few years took place in 2016, when HP acquired David Vision Systems and GE Additive bought both Arcam and Concept Laser. GE Additive actually wanted to buy SLM Solutions but was thwarted by a lack of shareholder support.

More recent M&A activity has seen companies acquired not just for their technology, but also for their talent, with the acquisition of Vulcan Labs by EOS being a good example of so-called 'acqui-hiring.'

In the thriving materials space, Henkel's acquisition of Molecule might be the precursor to other M&A deals.

The key M&A transactions associated with the 3D printing theme are listed in the table below.

| Date announced | Acquirer | Target | Value ($m) | Target company description |
|---|---|---|---|---|
| May 2019 | Henkel | Molecule | Not disclosed | Provider of 3D printing applications for several industries as well as inkjet resin technologies |
| Feb 2019 | EOS | Vulcan Labs | Not disclosed | Spin-off of Stratasys specializing in powder bed fusion technology. |
| Jan 2019 | Ansys | Granta Design | Not disclosed | Materials intelligence specialist provider of Granta MI and CES Selector products |
| Dec 2018 | Hobs Group | Canon UK 3D print unit | Not disclosed | Deal to acquire assets of Canon's 3D printer reseller business |
| Nov 2018 | Generation Growth Capital | 3rd Dimension | Not disclosed | Private equity acquisition of industrial precision metal provider |
| Sept 2018 | Kaiser Aluminum | Imperial Machine & Tool | Not disclosed | Multiple materials service provider ion 3D printing and machining technologies. |
| July 2018 | Prodways Group | Solidscape | Not disclosed | Stratasys wax 3D printing subsidiary |
| July 2018 | BASF | Advanc3D Materials | Not disclosed | Plastic powders for selective laser sintering |
| July 2018 | BASF | Set Up Performance | Not disclosed | Contract manufacturer for Advanc3D Materials |
| Mar 2018 | Mitsui Chemicals | B9 Creations | Not disclosed | Minority investment to strengthen dental technology and materials business ambitions |
| Mar 2018 | StructionSite | Rithm | Not disclosed | Provider of 3D laser scanning for construction quality assurance and quality control |
| Feb 2018 | Beamler | Printr | Not disclosed | Developer of enterprise resource planning cloud system for desktop 3D printers |
| Feb 2018 | SD3D Printing | 3D Matter | Not disclosed | 3D materials research specialist and provider of Optimatter material optimization software |
| Nov 2017 | Polar 3D | Makers Empire Pty | Not disclosed | Startup with software to help students translate design visions into printable 3D creations |
| Sept 2017 | Prasco | Apprecia Pharmaceuticals | Not disclosed | Manufacturer of 3D printed pharmaceuticals, including ZipDose technology |
| Aug 2017 | BASF | Innofil3D | Not disclosed | Premium filament maker |
| Aug 2017 | Prodways Group | AvenAo Industrie | Not disclosed | Specialist in integration of 3D applications including Dassault Systèmes' Solidworks |
| Feb 2017 | The Walt Disney Company | Makie Lab | Not disclosed | 3D printed and sold custom dolls company |

| Date announced | Acquirer | Target | Value ($m) | Target company description |
|---|---|---|---|---|
| Oct 2016 | The 3D Systems Corporation | Vertex-Global Holding | Not disclosed | Dental material solutions manufacturer of 3D biocompatible printable materials |
| Oct 2016 | SD3D Printing | Printgelize.com | Not disclosed | 3D printing services (consumer and businesses) |
| Oct 2016 | GE Additive | Concept Laser (75%) | 600 | Specialist in metals 3D printing, focusing on aerospace, medical and dental industries |
| Sept 2016 | GE Additive | Arcam | 685 | Manufacturer of electron beam melting metal 3D printers |
| Aug 2016 | WhiteClouds | Sandboxr | Not disclosed | 3D printer and software developer of video game collectibles |
| July 2016 | WhiteClouds | 3DPlusMe | Not disclosed | Provider of 3D ‘capture to print’ for big-brand toys, sports and action figures |
| June 2016 | HP | David Vision Systems | Not disclosed | Hardware and software solutions for optical 3D surface acquisition |
| May 2016 | Formlabs | Pinshape | Not disclosed | Online 3D printing community and marketplace (consumer grade) |
| Oct 2015 | Canon Medical Systems Corp | Olea Medical | Not disclosed | Post-processing and 3D visualization applications manufacturer |
| April 2015 | 3D Systems | Easyway Model Design | Not disclosed | 3D printing sales and service provider (automotive, medical and consumer goods) |
| Feb 2015 | Stratasys | Econolyst | Not disclosed | 3D printing and additive manufacturer (consultancy and research solutions) |
| Jan 2015 | 3D Systems | botObjects | Not disclosed | 3D printer manufacturer (business and home applications) |
| Nov 2014 | 3D Systems | Cimatron | 97 | CAD/CAM software (manufacturing, toolmaking, CNC programming applications) |
| Sept 2014 | Stratasys | GrabCAD | 100 | CAD company |
| July 2014 | 3D Systems | Simbionix USA | 120 | Virtual reality simulation products and solutions provider (clinical education and training) |
| Feb 2014 | Autodesk | Delcam | 286 | CAD/CAM software company (manufacturing industry) |

Source: GlobalData

## Timeline

The 3D printing industry has come a long way from its earliest days in the late 1980s. In 1993, the global printing marketplace was valued at just $100m. By 2013, it had grown to $3bn and, four years later, to $7bn. That figure is likely to grow to over $42bn by 2027, by which time 3D printing's role as a key part of the manufacturing mix will have been cemented.

The marketplace is already established enough – and has shown sufficient market growth potential – to persuade a number of chemical companies to wade in, increasing the array of materials options in both polymers and metals. HP's and GE Additive's moves into metal 3D printing are key developments in the industry's timeline.

By 2030, widespread disruption across a range of sectors – from aerospace to automobiles, consumer electronics to healthcare, and food to construction - can be expected as 3D printing industry revenues surpass $60bn.

**The 3D printing story**
How did the 3D printing theme get here and where is it going?

| | |
|---|---|
| 1988 | First commercial 3D printer developed by Chuck Hull, founder of 3D Systems. |
| 1993 | Global 3D printing market valued at $100m. |
| 1996 | 3D Systems sold its first 3D printer using a material jetting process, called the Actua 2100. |
| 2012 | Stratasys merged with Israel's Objet. |
| 2012 | Global 3D printing market valued at $2bn. |
| 2000 | Market grew to around £3bn. |
| 2014 | Chuck Hull was inducted into America's National Inventors Hall of Fame. |
| 2014 | 3D Systems unveiled its first kitchen-ready 3D printers for food. |
| 2014 | Share prices of 3D Systems and Stratasys peaked. |
| 2016 | GE bought Arcam and Concept Laser to create GE Additive, while HP bought David Vision Systems. |
| 2016 | Organovo announced plans to develop 3D bioprinted human liver tissue for direct transplantation to patients. |
| 2017 | Global 3D printing market valued at $7bn. |
| 2017 | HP entered 3D printing market. |
| 2018 | Chemicals companies, led by BASF, made concerted move into 3D materials market. |
| 2020 | First small-scale trials of bioprinted materials receive funding. |
| 2020 | First large-scale application of 3D printing in construction. |
| 2020 | GE Additive targets 3D printing revenues of $1bn. |
| 2021 | HP expects to make mark in metal 3D printing. |
| 2025 | Global 3D printing market is worth $32bn, according to GlobalData. |
| 2030 | Global 3D printing market is worth over $60bn, according to GlobalData. |

Source: GlobalData

# Value chain

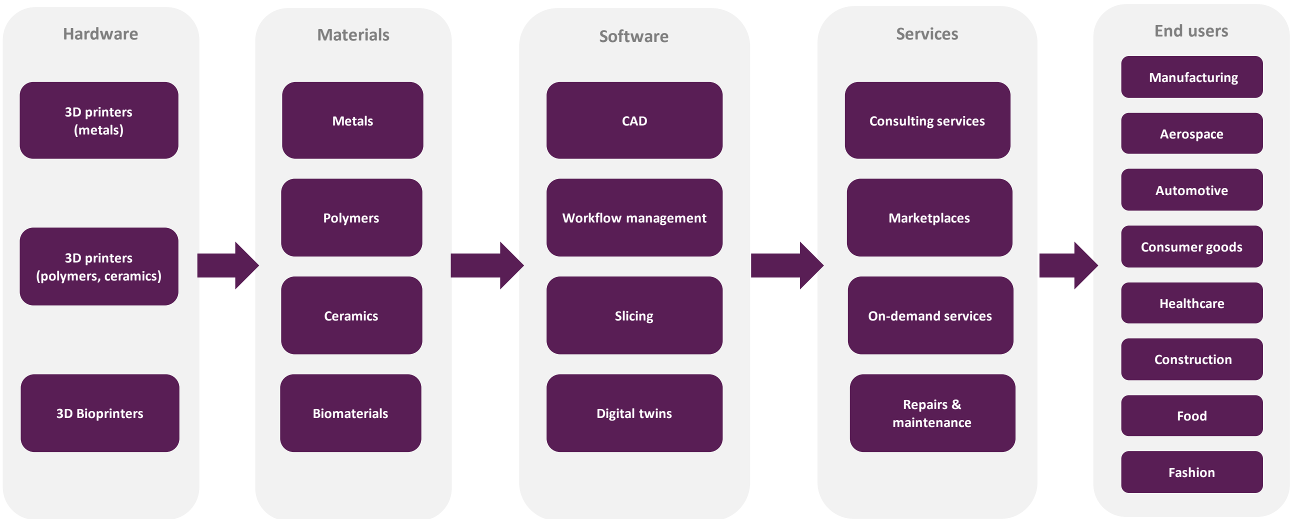
The value chain for 3D printing used to be relatively straightforward. It was divided into three core layers: hardware, software, and services. The hardware layer typically included both the physical machines that performed the printing, as well as the materials they used in order to create a 3D object but the increasing interest from chemicals companies in 3D printing has led to the creation of a separate materials layer.

The software layer incorporates the software products that are used to design objects for 3D printing, and particularly the software that is used to control the workflow of printers as they operate. Software also comprises digital twins, an area better known for its role in the Industrial Internet that is increasingly playing a key role in overseeing the 3D printing process by providing a view of both the design process and the production process, as well as an overall factory and machine management picture.

Finally, there are services, another growing area. The services layer used to comprise firms offering design and printing services to clients either in support of rapid prototyping, or as an element of the manufacturing process. Now, it may well include an array of consulting services, marketplaces, on-demand services, and repair services.

**The 3D printing industry value chain**

As the industry matures, new software and services elements are starting to emerge




Source: GlobalData

## Hardware

The hardware market for 3D printing is dominated by industrial systems, which account for around 70% of overall revenues. However, most printers sold fall into the personal printer segment of the 3D printing market which, after a few false dawns, is now in the middle of rapid and, it seems, continued growth.

3D printing is driving a quiet revolution in manufacturing. A key watchword in this transformation is design. That's because 3D printing's facilitation of fast design and quick prototyping is itself driving the adoption of fewer parts. GE Aviation's adoption of 3D printing to manufacture the fuel nozzles for its next generation of jet engines was a game-changer. The part was previously made with 18 separate components, but now GE makes it in one piece. It is 25% lighter and requires 80% less maintenance. As a result of the design driven by 3D printing, one engine's fuel consumption was reduced by 15% compared with its predecessor.

Although the fuel nozzle is one of the engine's tiniest parts, it is not just the weight of the part itself that has an impact. It is also the ability to fit that 3D printed part into the smallest of spaces, which consequently has an impact in reducing the overall weight of the system. It is the rethinking of design that 3D printing induces that results in significant change.

The real interest over the coming years is likely to be in the metal printing world, with market newcomers HP and GE Additive expecting to make their mark. HP believes it will be around two years before it is ready to attack the metal 3D printing market, while GE is aiming to reach $1bn in AM revenues by 2020. HP and GE have joined a cadre of 3D printing stalwarts, which includes 3D Systems, Stratasys, EOS, ExOne, Group Gorgé, and Renishaw.

Two companies to keep an eye on are Organovo and Desktop Metal. Organovo is the world leader in bio-printing (i.e. using live calls to create human tissue or organs). It has been developing liver tissue to treat a range of life-threatening diseases including end-stage liver disease, and it is now expanding the use of 3D bioprinted stem cell-based therapeutic tissues to applications aimed at treating end-stage renal disease. However, Organovo has so far failed to generate decisive scientific data supporting the prolonged functionality and therapeutic benefit of its lead therapeutic liver tissue candidate, and the company is now considering strategic alternatives. Another key player in the bioprinting field is EnvisionTEC,

Much is expected of Desktop Metal, which is a 3D printing unicorn: a startup with a valuation exceeding $1bn. Its original machine was a desktop model costing $120,000 which began shipping in 2018 and which was aimed at printing metal prototypes or lower-volume jobs. Its latest high-end machine costs more than $1m and is aimed at mass production. Desktop Metal's goal is to persuade the world's largest manufacturers that its machines can print fast enough and at a low enough cost to replace casting and CNC machining for metal parts. Along the way, it is likely to come up against its fellow Massachusetts based competitor, Markforged with the two companies already starting to get involved in legal battles with each other.

**3D printing hardware: leaders and challengers**

New names are arriving to challenge the 3D printing old guard in metals, polymers, and bioprinting

| Hardware | Leaders | | Challengers | |
|---|---|---|---|---|
| 3D printers (metals) | HP<br>GE Additive<br>3D Systems | Desktop Metal<br>Markforged<br>EOS | Stratasys<br>Renishaw<br>Carbon<br>SLM Solutions | Ultimaker<br>ProtoLabs<br>ExOne<br>Optomec |
| 3D printers (polymers, ceramics) | Stratasys<br>3D Systems<br>EnvisionTEC | HP<br>Carbon<br>Ultimaker | Formlabs<br>Prodways<br>Voxeljet | Markforged<br>EOS<br>XYZprinting |
| 3D Bioprinters | Organovo<br>EnvisionTEC<br>Cyfuse Biomedical | 3D Bioprinting<br>Regenovo Biotech<br>Aspect Biosysytems | BioBots<br>Rokit Healthcare<br>Cellink | |

Source: GlobalData

In the desktop systems space, key players are companies such as Ultimaker, Formlabs, XYZprinting, Aleph Objects and Zortrax.

## Materials

The materials world for 3D printing is thriving, with a number of players keen to take advantage of a rapidly growing industry. A number of chemicals companies – notably BASF and Henkel – have entered the market, supplementing the existing choice of materials providers. Other vendors keen to make their mark include Materialise, Solvay, Höganäs, Sandvik, Evonik, and GKN Power Metallurgy.

Partnerships between hardware and materials companies are growing. HP has a relationship with GKN on metals as part of a metal jet production service that allows customers to upload designs and produce production-grade additively manufactured metal parts in large quantities. The parts will be produced by HP partners GKN Powder Metallurgy and Parmatech, using HP's metal jet systems. GKN plans to use its metal expertise to engineer new powders based on customer needs and help them design previously unconsidered 3D printed parts.

In another link-up, Solvay and Stratasys are to work together to develop new high-performance filaments for use in Stratasys' FDM900 machine. As part of the cooperation, the two companies have worked to develop a filament based on a polyphenylsulfone (PPSU) polymer that will meet flammability requirements in aerospace applications. The new PPSU filament will be available in 2020.

Henkel has announced a partnership with the SYMPA research and development project which is working on new materials and stereolithography processes for the automotive sector, while one of the world's leading steel companies, ArcelorMittal, has joined IAM3D HUB, a shared work center for 3D printing in Barcelona.

In the medical world, titanium has previously been the default material for surgical tools and implants, but it is an expensive and complex process to produce titanium for 3D printing. Now, premium polymers such as PEEK and PEKK are being developed as an alternative.

Carbon fiber is also in demand as a material. Recent developments in printing technology have enabled companies to print with carbon fiber using a different binding material than standard carbon fiber processes. Resins do not melt, so they cannot be extruded through a nozzle. Instead, 3D printers substitute resins with readily printable thermoplastics.

There are two carbon fiber 3D printing methods in use, namely chopped carbon fiber filled thermoplastic and continuous carbon fiber reinforcement. Chopped carbon fiber filled thermoplastics are printed through a standard FFF (FDM) printer, and are made of a thermoplastic (polylactic acid, acrylonitrile butadiene styrene, or nylon) reinforced with chopped strands of carbon fiber. Continuous carbon fiber fabrication is a printing process that lays continuous strands of carbon fiber into a standard FFF (FDM) thermoplastic base.

Materials, as a definition, also includes what might be described as consumables, such as binder for the binder-jetting process.

**3D printing materials: leaders and challengers**

Chemicals companies are providing an array of materials to power 3D printing

| Materials | Leaders | | Challengers | |
|---|---|---|---|---|
| Metals, polymers & ceramics | GKN<br>BASF<br>Henkel | Solvay<br>Höganäs<br>Sandvik | Evonik<br>Stratasys<br>Voestalpine | Arkema<br>Mitsubishi Chemical<br>EOS |
| Biomaterials | Organovo<br>Cellink | | | |

Source: GlobalData

Bioink is the material used to produce engineered (artificial) live tissue using 3D printing. It is a combination of living cells together with a compatible base.

Organovo has a wholly-owned subsidiary, Samsara Sciences, dedicated to the isolation and characterization of primary human liver cells. Samsara serves as a source for the human liver cells that supports Organovo's in vitro liver tissue models and has a 'library' of primary human liver cells isolated from healthy and diseased tissue from a variety of donor backgrounds.

A key supplier of bioprinting materials is Cellink, which designs and develops bioprinting technologies, including a range of bioinks, ranging from those that are composed of the necessary particles to enhance bone tissue engineering applications to those able to recreate the natural wound-healing environment found in skin tissue.

## Software

3D printing software serves many different functions, from modelling to sculpting to workflow to customizing. Designs can be created on CAD software or they can be scanned into design software using 3D scanners.

The software used in designing something to be 3D printed depends on what you are trying to make. In general, 3D design software falls into two categories. The first is CAD software and the second is 3D modeling software. CAD software is usually used when creating industrial objects such as mechanical objects, while 3D modeling software allows for greater artistic freedom as designs do not need to work mechanically, be functional, or fit onto an existing device.

CAD software can be highly specific, providing a technical tool with functions in industrial design, mechanical design, architecture, and areas such as aerospace engineering and astronautics. A CAD model will also contain data like material properties, dimensions, tolerance, and manufacturing process-specific information. Creating a 3D printable model with CAD usually means saving the model in a stereolithography file format (STL), a de facto CAD file format for AM.

Examples of CAD software are TinkerCAD from Autodesk, Creo from PTC, Fusion 360, and SolidWorks from Dassault Systèmes. There are several examples of free 3D printing software that can help novices recreate real world objects without having to design from scratch, but CAD and project lifecycle management (PLM) tools tend to be more difficult to use.

As well as CAD and modeling software, there is also slicing software, which has been described as the middleman between the 3D model and the 3D printer. Typically, once you have modelled the object you would like to 3D print, it will be stored in an STL file. The slicer converts the model into a series of thin layers and produces a G-code file containing instructions tailored to a specific type of printer. Effectively, it is dividing the object into a stack of flat layers and describing these layers as linear movements of the 3D printer extruder, fixation laser, or equivalent. Strong players in slicing software are Ultimaker's Cura, which has an open source slicing engine, Autodesk's Netfabb, and Raise3D's ideaMaker. Both Slic3r and OctoPrint are also open source products

Key players in the software segment are familiar CAD players Autodesk, Dassault Systèmes and PTC. Siemens has a strong software heritage through its MindSphere Internet of Things (IoT) platform and, in working with HP, has discussed the application of digital twins thinking to 3D printing.

It is early days, but some vendors are also aiming software solutions at specific sectors. Materialise, for example, recently received US FDA clearance to produce a cardiovascular planning software suite aimed at supporting clinicians planning complex cardiovascular procedures. Another company with a growing reputation and client list is Markforged. It has launched an artificial intelligence (AI)-driven software platform which boasts a continuous feedback loop so that the printer learns from what it produces.

**3D printing software: leaders and challengers**

Elements include CAD, workflow management, slicing software, and digital twins

| Software | Leaders | | Challengers |
|---|---|---|---|
| Computer aided design | Autodesk<br>Dassault Systèmes<br>3D Systems | SketchUp<br>TurboCAD<br>PTC | Ansys<br>Paramatters |
| Workflow management | Adobe<br>Materialise<br>Autodesk | Stratasys (GrabCAD)<br>AMFG<br>Siemens | Authentise<br>3YourMind |
| Slicing | Ultimaker (Cura)<br>Simplify3D<br>KiSSlicer | Repetier<br>Slic3r<br>OctoPrint | Raise3D (ideaMaker)<br>Autodesk (Netfabb)<br>IceSL |
| Digital twins | Siemens<br>Dassault Systèmes<br>PTC | IBM<br>GE Additive<br>Ansys | |

Source: GlobalData

## Services

3D printing services have tended to be categorized into three sectors: resellers; printing services or on-demand printing; and online marketplaces, several of which have started to spring up.

In the on-demand world, the best known would be Shapeways, an online marketplace which allows the user to design, prototype and both buy and sell 3D printing products. Another familiar company in this space is Sculpteo. Other players here include i-Materialise and on-demand services provided by 3D Systems (QuickParts) and Stratasys (Stratasys Direct).

The growing maturity of the market and interest in metal 3D printing offers the prospect of an array of consulting services evolving, including consulting on design-for-additive as well as 'on ramp' and 'off ramp' services and, potentially, consulting around process control and developing the idea of digital twins.

Typical players in the consulting services field would be the large 3D printing players such as 3D Systems, Stratasys, HP, and GE Additive. Given its industrial heritage and knowledge of the digital twins space, Siemens is another notable vendor.

Another area of services that is set to grow in the future is repair services through 3D printing. A key player here is Optomec, which recently bought Huffman Systems to expand the use of 3D printing repair for the existing installed base of more than 100,000 gas turbines and engines.

**3D printing services: leaders and challengers**

Consulting and repair services will continue to grow

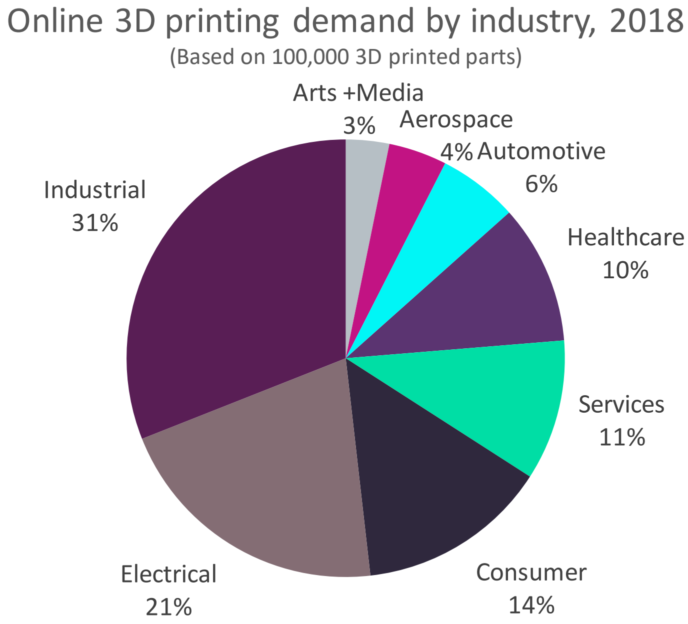
| Services | Leaders | | Challengers |
|---|---|---|---|
| Consulting services | Materialise<br>3D Systems<br>GE Additive | HP<br>Stratasys<br>Siemens | EY<br>Tata Consultancy Services<br>EOS |
| Marketplaces | Turbosquid<br>Pinshape<br>Sculpteo | Thingiverse<br>GrabCAD<br>MyMiniFactory | |
| On-demand services | iMaterialise<br>Shapeways<br>Sculpteo | ProtoLabs<br>Voodoo Manufacturing<br>QuickParts (3D Systems) | Stratasys Direct |
| Repairs & maintenance | Optomec<br>Stratasys<br>3D Systems | HP<br>GE Additive<br>EOS | Etsy |

Source: GlobalData

# How 3D printing is disrupting industries

In this section, we look at the key industries impacted by 3D printing and consider the prospect of continuing industry disruption as the AM marketplace continues to grow. This chart, of online 3D printing demand in 2018, based on a representative sample of 100,000 printed parts ordered by professional users in 2018, offers some insight into which industries are seeing the most 3D printing interest.

**Online 3D Printing provides a clue as to which industries are being most disrupted**
Industrial, electrical, and consumer sectors are the strongest adopters




Source: 3DHubs

Demand is relatively low in the aerospace and automotive industries, compared with the adoption of 3D printing in the industrial, electrical, and consumer goods sectors. However, the potential offered by those sectors is instructive.

By 2020, it is likely that the aerospace and automotive sectors will be in double figures, with the consumer goods share heading for 20%. Healthcare is likely to see significant demand as the wider potential for 3D printing becomes more widely understood. Other sectors too, including food, fashion, and construction, are likely to show up in greater measure in subsequent studies.

Here are how some key industries are being impacted by 3D printing with an estimation of the market impact.

## Manufacturing

While the jewel in the crown for 3D printing in manufacturing might ultimately be a significant presence in the automotive and aerospace industries, there is also a significant aftermarket where 3D printing is already playing a significant role, namely maintenance and repair.

Late in 2018, Optomec announced the acquisition of Huffman, which was regarded as the leader in supplying 3D metal printing systems for the additive repair of gas turbine components in the energy and aviation markets. Huffman's equipment and software is being used by major manufacturers of aircraft engines and industrial gas turbines, which utilize its metal deposition capabilities for the restoration and repair of worn or damaged components. Typically, they can do this at substantially lower cost than opting for newly-made spare parts.

Both Optomec and Huffman use the directed energy deposition (DED) method of 3D printing, which is regarded as a good solution for repair applications. It adds metal to existing parts that can then be milled or polished as necessary. It can also be used for coating applications that can extend the lifetime of components.

This marketplace for repair applications in industry is significant. Optomec has suggested that corrosion and wear costs the US economy alone $300bn a year, while the global commercial aviation industry spends almost $100bn annually on repair.

Optomec cites the example of the US Anniston depot using DED to repair engine components for the M1 Abrams tank. Operating in a desert environment, tank engines such as the Honeywell AGT 1500 were experiencing extreme amounts of wear, requiring shorter interval maintenance cycles. The AGT 1500 components are difficult to repair with traditional methods due to distortion effects caused by the high-heat welding process. With DED, a highly-focused laser beam delivered energy exactly to the repair area and, since the process has an extremely small heat-affected zone, few residual stresses remained and distortion was negligible. This allowed the Army to repair rather than replace worn engine components, saving over $5m per year.

In another example, a New Mexico salsa factory has also used DED processing for repair applications. When the salsa production line was shut down due to a broken helical gear, no spare gears were in stock and there was an eight-week lead time to deliver a replacement, which would have meant a significant loss in production capacity during the busy holiday season. Using DED, the Inconel helical gear was repaired and the production line was back in operation within one day.

**3D printing repair of a gear using DED**

Before: broken gear teeth


After: gear with 3D printed repair

Source: Optomec

## Automotive

The automotive sector should be ripe for 3D printing. The demand for electric vehicles as a counter to pollution amid environmental concerns, plus tightened production cycles, has led to a need for the design process to be speeded up while costs are cut. However, regulatory issues around widespread use of 3D printing remain a concern. That said, there is significant usage of 3D printing now underway in the automotive sector and a desire to track 3D printing progress closely.

Stratasys has suggested there are several applications for 3D printing in the automotive sector, such as using fused deposition modeling to create new tooling for short-run testing or production parts, customizing vehicle interiors, or making measurement and production devices such as jigs. Stratasys' automotive clients include the Fiat Chrysler Group, Volkswagen, and Ford, as well as luxury brands, such as Lamborghini and Ferrari.

In one application, Bentley Motors used Stratasys PolyJet technology to create a future production vehicle in miniature. The 3D print process enabled designers to test multiple forms and a variety of practical functions, bringing them closer to a final design much more quickly than in the past.

Stratasys also worked with Jaguar Land Rover to produce a complete fascia air vent assembly for a Range Rover Sport. In a single process, Jaguar Land Rover printed the complete fascia air vent as a working part. Once printed, the model was taken from the printer, cleaned, and tested, proving that the hinges on the blades all worked and the control knob had the right look and feel.

Rapid tooling has also become a focus for many automotive companies, with a key application being the use of pre-series molds, produced with a 3D printer, and then doing the first 50 to 200 design iterations for the tooling. Engineers typically evaluate the molds to determine the optimal design before creating a steel version for a final mold. Designing tooling with 3D printing additive from the start removes multiple steps and cuts costs compared with traditional tooling methods.

3D printing can also play a role when it comes to measurement and parts assembly in the automotive world. One tier one automotive supplier worked with Stratasys engineers to develop a multifunctional tool that can measure several points on a headlight or taillight prior to final assembly in a plant in Germany. The tool, which was printed with FDM technology, marries three different measurement steps into one, and replaces tools made with steel or aluminum, that have less functionality, while at the same time reducing costs by two-thirds.

Beyond the above use cases, it is even possible to consider using 3D printing to create a complete car. Italian electric car company XEV and 3D printing material company Polymaker have produced what they claim is the world's first mass-producible 3D printed electric car.

**Creating a 3D printed car**

Italian company XEV's electric car has just 57 parts

Source: Polymaker

XEV decreased the plastic parts and number of components in a car from more than 2,000 to 57, with the finished low-speed electric vehicle (LSEV) weighing only 450 kilograms, compared to similar sized vehicles that usually weigh between 1 and 1.2 metric tons.

Apart from the chassis, seats, and glass, all the visible parts of the car are made by Polymaker materials through 3D printing. This switch of production leads to a more than 70% reduction in investment cost when compared with a traditional production system.

The vehicle takes around three days to make and costs around $7500. It has a top speed of about 43 miles per hour and can travel about 93 miles on a single charge. XEV had said it intended to start production of the vehicle in the second quarter of 2019, with initial orders for 7000 vehicles in place.

## Aerospace

The aerospace sector is becoming a serious exponent of 3D printing with both major aircraft manufacturers, Boeing and Airbus, adopting the technology. Boeing says it now has over 20 years' experience in 3D printing, having realized early on that the technique could save it energy, time, and costs. Its 777x plane incorporates the world's largest solid 3D printed item, a wing trim and drill tool measuring 17.5 feet long, 5.5 feet wide and 1.5 feet tall. Using 3D printing cut the time needed to create the item from several months to about 30 hours.

Meanwhile Airbus plans to use desktop 3D printing company Ultimaker to supply it with 3D printers, Ultimaker Cura software, and materials to use in its European facilities. Airbus will mainly use the Ultimaker portfolio for the direct, local production of tools, jigs, and fixtures, and printing lightweight design parts with composite materials.

Airbus had earlier completed a study of the effectiveness of 3D printing on a highly standardized part, an Airbus A320 nacelle hinge bracket. The test compared another supplier, EOS's titanium printed bracket using direct metal laser sintering, with a traditionally-cast steel bracket. Airbus found that EOS's 3D printed bracket was stronger, lighter, and produced 40% fewer CO2 emissions during manufacture. It also eliminated waste from secondary machining, reducing titanium consumption by 25%.

**GE's 3D printed fuel nozzle for the LEAP engine proved the technology's use in aerospace**

20 parts were combined into a single printed unit that weighed 25% less than an ordinary nozzle.

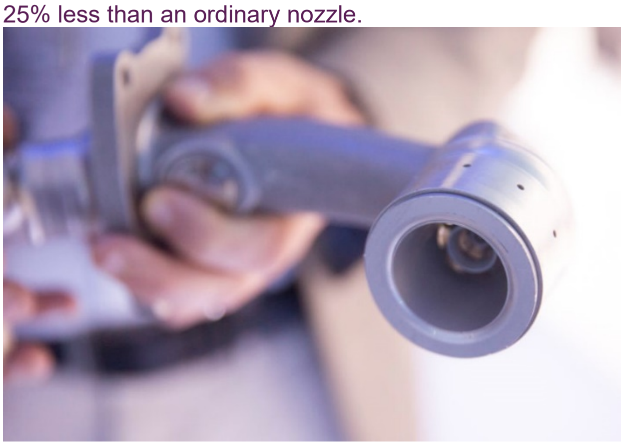


Image credit: Adam Senatori for GE Reports

The real success story in aerospace, and arguably the one that pointed the way for other user cases, was GE Aviation's use of 3D printing which led to the creation of GE Additive. GE Aviation's use of a 3D printed nozzle inside the LEAP (Leading Edge Aviation Propulsion) engine broke new ground and led to the LEAP becoming one of the best sellers in the history of CFM International, a joint venture between GE Aviation and France's Safran Aircraft Engines. The company used a local Cincinnati company, Morris Technologies, to 3D print a complex nozzle, while in the process combining 20 parts into a single unit that weighed 25% less than an ordinary nozzle and was more than five times as durable.

GE's engineers then moved on to the next challenge. A different team decided to create a new advance turboprop engine, or ATP. Using AM, GE consolidated 855 components into just a dozen parts. The simpler design reduced weight, improved fuel burn by as much as 20%, and also achieved 10% more power. Using 3D printing for rapid prototyping, the team was also able to cut development time by a third.

Having proved that 3D printing could be used to 3D print a complex jet engine muzzle, GE Aviation then started to try and find other applications that could use the technology. Six GE engineers set out to find what portion of an old commercial helicopter engine could also be 3D printed. Within 18 months, the team found it was able to print half of the machine, reducing 900 separate components to just 16, including one segment that previously had 300 different parts. The printed parts were also 40% lighter and 60% cheaper. Having proved the technology could work, the group got the support of GE Aviation president and chief executive David Joyce and the GE Board. Ultimately the development led to the creation of GE Additive and the acquisition of 3D printing companies Arcam and Concept Laser.

## Consumer goods

From personalized razor handles to bike helmets, eyewear to 3D printed insoles for customers' feet, 3D printing has a growing range of consumer goods applications. 3D printing offers consumers the prospect of personalized experiences, and now, consumer companies have spotted the potential.

For example, shaving products company Gillette has launched a Razor Maker platform through which customers can choose razors that best suit their budget and preferred style. Gillette is piloting the platform with the help of desktop 3D printing company Formlabs, with customers able to pick from 48 design options produced using stereolithography.

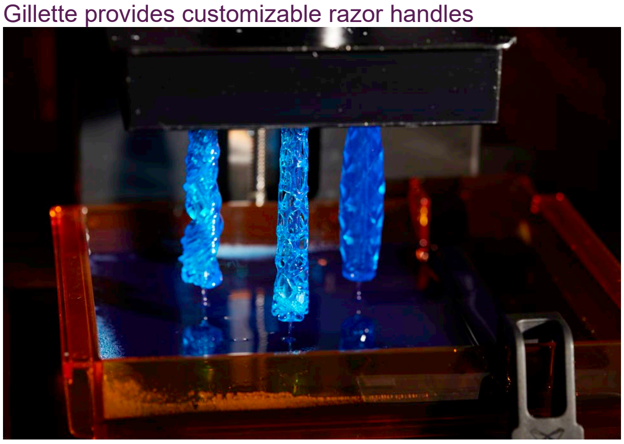
The same customization story applies to sports shoe wear. Adidas is partnering with Carbon to manufacture Futurecraft 4D, a new line of athletic shoes for the mass market with 3D printed midsoles that will eventually be customizable. Where Adidas goes, rivals such as Nike, New Balance, and Under Armour are likely to follow.

Footcare company Dr Scholl is following in Adidas footsteps. It is working with technology company Wiivv to make custom 3D printed inserts. Dr Scholl's customization app creates a scan of customers' feet and then uses the scanning technology within the app to create custom insoles, based on hundreds of mapping points from each foot.

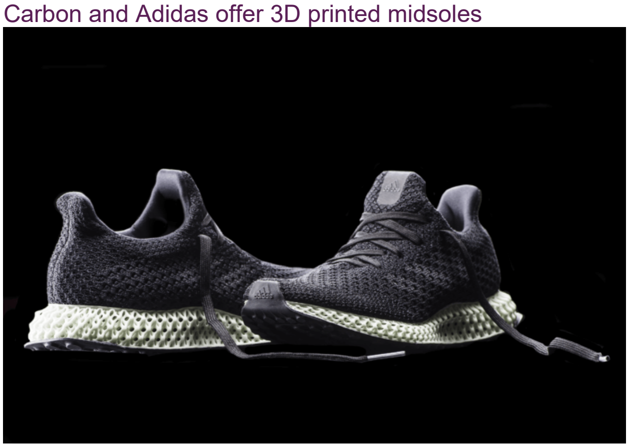
In the future, the advent of 4D printing might allow the customer to go even further down the customization route. Imagine being able to make your favorite pair of jeans last forever, thanks to self-repairing polymer chains in the fabric.

**3D printing provides customers with personalization options**

Gillette provides customizable razor handles



Carbon and Adidas offer 3D printed midsoles



Source: Gillette, Carbon

## Healthcare

The market for 3D printing in healthcare is a growing one, driven by the demands of an ageing population that is living longer in many countries, with a consequent increase in demand for dental work and devices such as hearing aids or implants.

3D printing is playing a growing role in medical training – such as the 3D printing of organs – or even on the operating table, where 3D printed tools can guide surgeons.

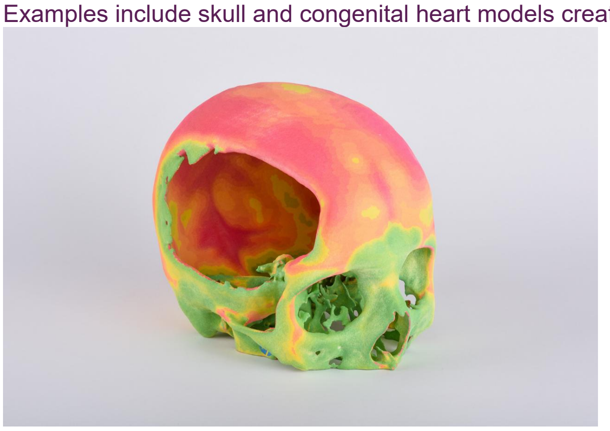
In one of the most recent high-profile examples, 3D printing was used to help separate conjoined twins. Surgeons at Great Ormond Street Children's Hospital performed the complex surgery in three stages over five months, having used 3D printing to create models of the two girls' brains.

The demands and potential of the medical market has got materials and systems players working together to ensure their solutions are compatible with healthcare markets.

Materialise and HP, for example, are collaborating to ensure that HP Jet Fusion 580/380 printers will work with Materialise's Mimics image processing software technology, to be able to print robust full-color anatomical models for diagnostic and surgical planning processes. This includes cardiac, orthopedic and cranio maxillofacial models, complete with vascular structure, that have been historically difficult to 3D print.

**3D printing is being used to create models that can aid surgeons in operations**

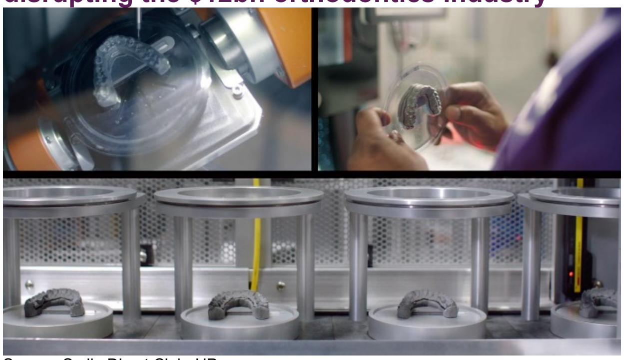
Examples include skull and congenital heart models created using Materialise's Mimics software



Source: HP, Materialise

In the US, Smile Direct and Align Technology are using 3D printing as part of a business model that uses a digital solution to straighten teeth. Smile Direct is working with HP, while 3D Systems has partnered with Align. One recent estimate put Smile Direct's market value at around $3bn, largely based on its 3D printing approach.

**Smile Direct's approach to teeth-straightening is disrupting the $12bn orthodontics industry**



Source: Smile Direct Club. HP

Smile Direct Club's direct-to-consumer approach to teeth-straightening uses 3D printing technology from HP to produce more than 50,000 unique mouth molds a day using HP's Jet Fusion 4210 3D printers. The company first takes a mold of its clients' teeth. The 3D impression is then reviewed by an orthodontist, who creates a treatment plan. Smile Direct Club then sends the aligners. Customer can purchase a set of retainers for $99. The entire process costs less than half that of a traditional teeth-straightening process. An estimated 80% of Americans could benefit from orthodontic care, yet only 1% receive it each year, with cost being the biggest prohibitive issue.

## Construction

As in many of the sectors in which it is taking off, 3D printing is threatening to overturn the conventional approach to construction modeling and housing design.

The technology makes it possible to create complex shapes and, at the same time, cut production times, and reduce costs and waste, while also limiting heavy manual work and accidents.

Construction company Bouygues, for example, believes that 3D printing, used as part of a digital modelling approach, could push back the limits of construction and pave the way for the most complex architectural shapes. In 2017, Bouygues and Nantes University joined forces to build the first 3D printed house, in Nantes. Other organizations have made similar claims. One is Apis Cor, which has 3D printed a house in Moscow. It is also competing in a competition run by NASA called the 3D Printed Habitat Challenge, to create sustainable shelters suitable for the Moon, Mars, or beyond.

**3D printing expands the limits of construction**

Apis Cor is applying 3D printing to construction

Bouygues built this 3D printed house in Nantes

Source: Apis Cor, Bouygues

## Jewelry

Jewelry-making is an ancient craft which is now being enabled by 3D printing, typically by using FDM and SLA printing processes. 3D printing is more usually adopted to make plastic prototypes of jewelry before they are sent for final design and production, but there is now a move into the manufacturing of finished jewelry. Although many would consider a 3D metal printer to be expensive, and it is certainly unlikely that one would be used for home-based printing, there is a belief that, in the future, 3D printing is going to be a realistic option to create jewelry.

The future could see customers using 3D jewelry printing services to print custom-made designs, new designers being able to break into the market by manufacturing larger quantities of their own designs, or the development of jewelry-specific online marketplaces, making it easier for new designers to sell their wares.

Cooksongold, a one-stop shop for jewelry makers, has been working with EOS to showcase technology for the jewelry and watch industry. Cooksongold has developed a series of precious metal powders to ensure that the powder composition, flow characteristics, and particle size distributions optimize performance in the EOS M 100 system for the platinum, gold, and silver alloys available. The designs shown below were designed by Within Technology and Towe Jewels and manufactured using Cooksongold's 3D printing technology.

**3D printing techniques are now being used to create jewelry**

Jewelry designed by Within Technology

Bangle designed by Towe Norlen of Towe Jewels

Source: Cooksiongold

## Food

Chocolate, sugar and pasta are just some of the ingredients that can be 3D printed to create edible food products and the techniques are already well-tested. For example, in 2014 pasta-maker Barilla organized a contest to choose the best 3D model design for a new Barilla pasta. Designers from 20 different countries submitted 216 pasta proposals, with the winning design sold by Barilla as a new product.

**BeeHex is a 3D printing spin-off from NASA**

3D printing food is a solution for deep space missions

Source: BeeHex

Other organizations that have worked on food 3D printing include US chocolate maker Hershey, which began a collaboration with 3D Systems to explore ways of making edible products, and Natural Machines, which produces a food 3D printer that allows users to print their food in precise portions and shapes. It has its own print application, Foodini Creator, with shape libraries to start designs and recipes or create them from scratch. One company, BeeHex, which decorates biscuits and cakes, was created by an engineer working with NASA to build a device capable of 3D printing food for deep-space missions. There are already food 3D printing conferences, with one now in its fifth year.

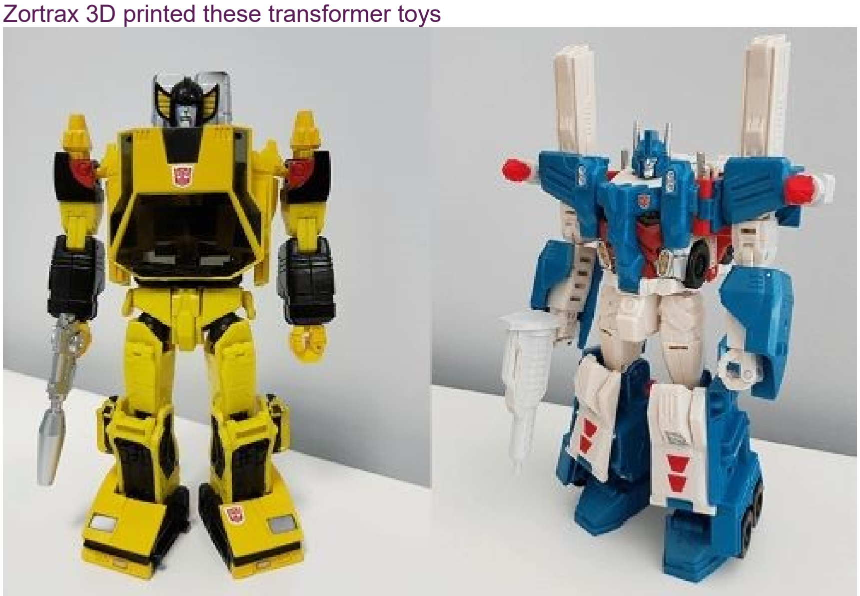
## Toys

The toy industry is another market that faces significant disruption from 3D printing. Many toys are made out of plastic, which means that 3D printing offers a clear opportunity to repair broken toys or replace missing ones. 3D printing services from companies such as Thingiverse or Shapeways can be used to make toys from 3D files.

Typical parts for toys, such as Lego, can be improved or replaced through the Shapeways service. Shapeways, for example, offers Lego-compatible helical gears “3D printed in black nylon plastic with a matte finish and slight grainy feel.”

**The toy industry is also in danger of disruption from 3D printing**

Zortrax 3D printed these transformer toys



Source: Zortrax

Toy manufacturers are also making use of 3D printing in their production processes. Like other industries mentioned above, toymakers can 3D print prototypes of toys, enabling them to control the quality of a design and compare different versions while verifying that the toy parts fit well together. Such a means of verifying the quality of products means they can identify potential issues earlier and more cheaply.

Late in 2018, Lego Group said it had invested in 3D printing firm Evolve Additive Solutions.

The partnership will mainly see Evolve’s technology being used to create prototypes in the development of new products. Lego said it had no plans to launch 3D printed Lego bricks or elements commercially, adding that it will continue to use additive manufacturing in its innovation pipeline to create fast prototypes. It said injection molding technology remains core to the large-scale production of LegoBricks. The collaboration with Evolve, it said, is an example of how it partners with leaders in technology to inspire and develop new thinking.

# Companies

In this section, we highlight the listed companies and private companies that are making their mark within the 3D printing theme.

## Public companies

The table below lists some of the leading listed players impacted by the 3D printing theme and summarizes their competitive position in the theme.

| Company | Segment | Country | Competitive position in the 3D printing theme |
|---|---|---|---|
| **3D Systems** | Hardware<br>Materials<br>Software<br>Services | US | Late in 2018, 3D Systems announced new additions to its DMP metal 3D printing platform, designed for volume production of critical components in the aerospace, healthcare, and transportation sectors. It also introduced a new aluminum alloy material designed to produce strong, lightweight parts without the need for casting. 3D Systems has a growing partnership with machining group Georg Fischer intended to enhance metal parts production and redefine how manufacturers think about their manufacturing environments. The two companies have been working on integrated solutions for factory automation that include software for enhanced part design, 3D printers, materials and automated material handling, milling equipment and advanced post-processing technologies. 3D Systems also has a prominent position in providing 3D printing systems for dental professionals, including the NextDent 5100 printer. |
| **Adobe** | Software | US | In April 2010 Adobe released Adobe Photoshop CS5 Extended which included the Repoussé, a tool that enabled the creation of 3D objects extruding texts, selections, paths, and layers masks. Adobe has since unveiled an update to Photoshop CC (Creative Cloud) with the hope that it will allow designers to create a model from scratch or refine an existing design leading to perfect print-ready 3D models. One of the most common problems with 3D printing is human error in virtual modeling, so Photoshop includes automatic mesh repair and can insert a support structure to ensure that the model will print reliably without faults. Photoshop CC enables the creation of a 3D design from scratch, with subsequent links to a range of 3D on-demand printers, including Shapeways, Sculpteo, i-Materialise, 3D Hubs, Stratasys Direct Manufacturing, and Ultimaker. |
| **Ansys** | Software | US | Engineering simulation software specialist Ansys has included 3D printing in a new generation of capabilities in its software suite. It has an Additive Print standalone solution, created with design for additive manufacturing (DfAM) designers and AM machine operators in mind. It also offers a layer-by-layer metal powder bed simulation tool to help eliminate failed builds and physical trial and error, which can be integrated into designers' and AM machine operators' workflows. There is also a Workbench Additive solution so that engineering analysts can remain within the Ansys Workbench environment throughout the simulation process. |

| Company | Segment | Country | Competitive position in the 3D printing theme |
|---|---|---|---|
| **Autodesk** | Software | US | Autodesk's various CAD packages, such as AutoCAD, NetFabb, Within Medical, Fusion 360, TinkerCAD, and 3DSMax, play an important role in 3D printing. Looking to the future, Autodesk believes a rising global population will lead to increased demand for buildings and, with a short supply of qualified workers, it believes the construction industry will need to consider new building techniques, including the way parts of buildings are made. Its solution is a combination of robots and 3D printing, in the form of a toolbox for construction sites. The idea is that the robots and printing systems, which are able to print large, usable metal components, can be packaged in the container and sent from one job-site to another. This method is intended to enable buildings to be built more quickly and parts to be produced more accurately, while at the same time tackling the construction labor shortage. |
| **BASF** | Materials<br>Services | Germany | BASF's acquisitions of Advanc3D Materials, Set Up Performance, and Innofil3D have enabled it to lead the charge of chemicals companies into the 3D printing marketplace. BASF has struck deals with several partners for its powders, including HP for its Multi Jet Fusion printers. Ultrasint TPU01 is only processable in HP Multi Jet Fusion printers and is suited for producing lattice structures. BASF 3D Printing Solutions (B3DPS) has also entered into a strategic partnership with the US company Origin, for the further development of photopolymer printing processes, and with Photocentric, a manufacturer of 3D printers and their corresponding software and materials, around the development of new photopolymers and large-format photopolymer printers for the mass production of functional components. Innofil3D is also entering into a partnership with China's Jet-Mate Technology, for the distribution of plastic filaments. |
| **Dassault Systèmes** | Software | France | Dassault Systèmes has an on-site and cloud-based software solution for businesses that require 3D design. The software program, 3DExperience, incorporates apps for content and simulation, information intelligence, social collaboration, and 3D modelling. It also has a range of programs, including 3D design software, such as Solidworks and Catia. Dassault has also launched a cloud-based marketplace for on-demand manufacturing, intended to provide an online ecosystem for industrial services and content providers. The 3DExperience marketplace was launched with 50 digital manufacturers providing 500 machines and 30 million components from 600 suppliers. The marketplace features a 'make' option, so users can get parts made by digital manufacturers online across all manufacturing processes, from 3D printing to CNC machining and injection molding. |

| Company | Segment | Country | Competitive position in the 3D printing theme |
|---|---|---|---|
| **ExOne** | Hardware<br>Materials<br>Services | US | ExOne recently announced collaboration relationships with AM materials company Sandvik and with Siemens to implement its digital enterprise portfolio of software and automation technology, including MindSphere on ExOne's new S-Max Pro sand printer. The Siemens digital enterprise portfolio incorporates a digital twin approach that uses a shared data model alongside the entire value chain covering machine simulation, engineering, and commissioning to operations and services. The Sandvik relationship will focus on qualifying and optimizing Sandvik's Osprey metal powders with ExOne's binder jetting machines. The collaboration will include studying powder and binder interactions, developing 3D machine process settings, and creating post-processing heat treatments for various materials, initially including stainless steels, tool steels, and nickel alloys. Sandvik already houses multiple ExOne systems in-house and is a beta customer for its recently launched X1 25PRO machine. |
| **Faro Technologies** | Software | US | Faro is in the business of 3D measurement, imaging, and realization technology. It develops and manufactures solutions that enable high-precision 3D capture, measurement, and analysis across a variety of industries, including manufacturing, construction, engineering, and public safety. It recently released a new metrology software platform, CAM2 2019, designed to enable users of Faro metrology hardware products to realize higher levels of measurement performance across the automotive, aerospace, machine tools, metal fabrication, and other manufacturing industries. |
| **GE** | Hardware<br>Materials<br>Software<br>Services | US | Having seen the benefits of the technology in nozzles for jet engines, GE has bet big on 3D printing, spending $1.4bn in 2016 to acquire metal AM leaders Arcam and Concept Laser. It ultimately hopes to generate $1bn of revenues from 3D printing by 2020, in part by leveraging adoption across the wider GE group. In June 2019 it announced that GE Aviation had made a significant investment in electron beam melting (EBM) technology with the purchase of an additional 17 A2X systems and 10 Spectra H systems. Avio Aero, a GE Aviation company, currently operates a fleet of 35 Arcam machines at its recently expanded site in Italy. The additional EBM systems will be installed at GE Aviation and Avio Aero facilities in the US and Europe and will be used primarily for the production of titanium aluminide (TiAl) blades on the low-pressure turbine for the GE9X engine. 3D printed TiAl blades are roughly half the weight of traditional nickel-alloy turbine blades. GE Additive Arcam EBM A2X machines produce six blades per batch, while the Spectra H system can produce up to 10 blades in around the same time. In 2018, GE Additive received $9m from the US Office of Naval Research to develop a process for creating 1:1 scale twin digital models of metal 3D printed parts for the US Navy. |

| Company | Segment | Country | Competitive position in the 3D printing theme |
|---|---|---|---|
| **Groupe Gorgé** | Hardware<br>Materials<br>Services | France | Groupe Gorgé operates in the 3D printing market through its subsidiary, Prodways Group. Prodways' various businesses in its systems division cover 3D printers and related materials (Prodways Technologies); liquid and medical resins (Deltamed); polymer powders (Exceltec); and the integration of 3D design software (AvenAo). Through its products division, Prodways develops its own manufacturing for the podiatry (orthopedic insoles), dentistry (orthodontic pieces and dental trays), and earmolds (custom earmolds and hearing protection) markets in which it sells directly to healthcare professionals. |
| **Henkel** | Hardware<br>Materials<br>Services | Germany | Adhesives specialist Henkel started moving into 3D printing in 2016. As a supplier of hotmelt and high performance adhesives used in applications such as medical and electronic devices, it set out to expand its product range by introducing novel light cure resins, which were commercialized in 2017. Henkel's hotmelt adhesives have already been used in the 3D printing of functional applications such as furniture and it is focusing development in this area on providing novel filament and powder materials for SLS and FDM printers. In May 2019 it acquired Molecule, a privately owned company focused on product innovation in AM. Molecule provides advanced solutions for 3D printing applications, including medical devices, aerospace, automotive, and consumer goods, as well as industrial inkjet materials. In 2018, Henkel opened an innovation center for 3D printing in Dublin, as part of an €18m, four-year investment plan. |
| **HP** | Hardware<br>Materials<br>Software<br>Services | US | HP's acquisition of David Vision Systems in 2016 set it on a path to try and make 3D printing as much of a business for the company as 2D printing. 3D printing now accounts for a fraction of HP's close to $60bn revenues, but it has been described as the future of the company. HP has built partner agreements with companies such as Materialise, GKN, and Siemens to help it accelerate a path to significant revenues. It has bet heavily on multi jet fusion technology and its Jet Fusion 500/300, 4200 and new 5200 machines. But the company admits it is two years away from having a metals printing proposition. It has created a Digital Manufacturing Network, picking partners based on their end-to-end 3D printing skills for production at scale, and their manufacturing and quality processes. They include Parmatech, GoProto, Zigg Zagg, Materialise, Forecast 3D and Jabil. |
| **Materialise** | Materials<br>Software<br>Services | Belgium | Materialise has combined the largest group of software developers in the industry with one of the largest 3D printing facilities in the world. Materialise was one of the first to explore new applications and offer manufacturing services based on HP's Jet Fusion 5200 Series printers, as part of a collaboration that also involves Nikon and Essentium. Materialise is also working with customers to develop solutions for HP's new certified thermoplastic polyurethane (TPU) material, developed by BASF. Its Materialise Magics software suite is used for data preparation for 3D printing, for control of 3D printing machines, and for managing the 3D production process. Materialise has also launched a Mimics Care Suite as a platform for image-based planning and medical 3D printing in hospitals. |

| Company | Segment | Country | Competitive position in the 3D printing theme |
|---|---|---|---|
| **Nano Dimension** | Hardware<br>Materials<br>Software<br>Services | Israel | Nano Dimension's 3D printing expertise is as a disruptor of how connected electronic products are made. It offers the DragonFly Pro system for the 3D printing of electronics, including the simultaneous 3D printing of dielectric polymer and conductive metal. It argues that the 3D printing of functional electronics, essential to these industries, can be prototyped more quickly and securely in-house than ever before, with lower costs. Nano Dimension recently entered the Japanese market with the sale of a DragonFly printing platform to CMK, one of Japan's largest printed circuit board (PCB) manufacturers. CMK will use the DragonFly Pro multi-material AM system for faster prototyping cycles of printed wiring boards during early development. |
| **Organovo** | Hardware<br>Services | US | Organovo is the 3D printing company most closely associated with the 3D bioprinting of tissues that mimic key aspects of human biology and disease with a goal of pioneering therapeutic and drug profiling capabilities. It has been developing liver tissue to treat a range of rare, life-threatening diseases including end-stage liver disease and a select group of inborn errors of metabolism (IEMs). Organovo hoped it could serve as a bridge to transplant for patients with limited treatment options by restoring function, or offsetting the deficiencies related to a specific condition, but, in August 2019, the company revealed that it had not generated decisive scientific data supporting the prolonged functionality and therapeutic benefit of its lead therapeutic liver tissue candidate, adding that redevelopment of the tissue would require significant time, additional resources, and development risks, and would probably not provide sufficient return on investment for Organovo's stockholders. The company is now considering strategic alternatives and has implemented a restructuring plan to reduce expenses. Those strategic alternatives include the potential for an acquisition, merger, reverse merger, business combination, sale of assets, licensing, or other strategic transaction. |
| **Protolabs** | Hardware<br>Materials<br>Services | US | ProtoLabs was founded to radically reduce the time it took to get injection-molded plastic prototype parts. Its solution was to automate the traditional manufacturing process by developing complex software that communicated with a network of mills and presses. As a result, plastic and metal parts could be produced much more quickly than before. In 2014, it launched industrial-grade 3D printing services to allow product developers, designers, and engineers an easier path to move from early prototyping to low-volume production. Protolabs claims to be the world's fastest manufacturer of custom prototypes and on-demand production parts with manufacturing facilities in eight countries. It argues that it can produce commercial-grade plastic, metal, and liquid silicone rubber parts within days. |

| Company | Segment | Country | Competitive position in the 3D printing theme |
|---|---|---|---|
| **PTC** | Software | US | PTC has a 3D CAD solution, Creo, which enables organizations to design, optimize, validate, and run a print-check all in the same environment, before sending the file to the printer. Creo can be used for design both in polymers as well as metals. Late in 2018, PTC spent $70m to acquire Frustum. The acquisition was intended to add Frustum's generative design technology to the PTC Creo CAD portfolio. Earlier in 2018, PTC partnered with Belgian 3D printing company Materialise to increase the 3D printing capabilities of PTC's Creo suite. The solution will offer manufacturers a connection between PTC's software and 3D printing machines equipped with a Materialise Build Processor. |
| **Renishaw** | Hardware<br>Materials<br>Software | UK | Back in 2013, Renishaw, at the time the UK's only manufacturer of an AM machine that printed metal parts, was the major sponsor of an exhibition being held at the Science Museum in London, which explored the future for 3D printing. The company recently collaborated with two advanced technology companies, Irish Manufacturing Research (IMR) and nTopology to demonstrate the advantages of AM in the production of spinal implants. Renishaw also recently introduced a new 3D printing system, the RenAM 500Q, which includes four 500-watt lasers in the most commonly-used platform size. It argues that by speeding up the AM build process, manufacturers will see a drastic increase in productivity, leading to a reduction in cost-per-part, an increase in return on investment, and a reduction in process waste. Renishaw also wants to ensure there is greater certification in the 3D printing process and so has made appropriate upgrades to its InfiniAM Spectral software. |
| **Siemens** | Hardware<br>Materials<br>Software<br>Services | Germany | Siemens' digital enterprise suite is widely used to provide supporting software for 3D printing and it has relationships with many of the key 3D printer companies, including HP and ExOne. The suite is based on Siemens PL software solutions, including NX, its integrated CAD/CAM/CAE solution; the Simcener solution portfolio, a simulation and testing program; Teamcenter, a digital product lifecycle management system; Simatic IT and Simatic WinCC, two products from the Siemens manufacturing operations management (MOM) portfolio for production; and MindSphere, its cloud-based, open IoT operating system. Last year Siemens opened a new 3D printing facility in the UK. The 4,500 square meter facility enables the company to expand its capacity to 50 machines, which will produce high-end serial parts for Siemens Power and Gas and customers in the aerospace, automotive, motorsport, and other industries. As a specialist in the concept of 'digital twins', Siemens offers a simulation solution that creates digital twins of 3D-printed metal objects, making it possible in advance to identify potential deformation during production and to modify the object before printing. |

| Company | Segment | Country | Competitive position in the 3D printing theme |
|---|---|---|---|
| **SLM Solutions** | Hardware<br>Software<br>Materials<br>Services | Germany | In May 2019, SLM Solutions reported results from the first quarter of 2019 which caused it to question its strategy. New order intake dropped to seven machines from 15 in the first quarter of 2018, while the value of orders received was 60.5% below the value of orders received in the same period of the previous year. Planned framework agreements in China did not generate the orders expected and have since been put off. The company described the results as “well below our expectations.” SLM has a new chief executive in Meddah Hadjar, formerly of GE Additive, which is somewhat ironic given that SLM was targeted for acquisition by GE in 2016. Having been told that its bid was not in the interests of SLM shareholders, GE walked away and instead bought Concept Laser, one of SLM’s German competitors. If the second half of 2019 is as bad as the first, SLM Solutions might find itself an M&A target again. |
| **Stratasys** | Hardware<br>Software<br>Materials<br>Services | US | Stratasys has been in 3D printing for over 30 years. It recently adopted Sapphire 3D print systems and Flow software by Velo to further diversify and enhance its additive metals offerings. It means the direct manufacturing branch of Stratasys will be able to print complex geometric metal parts with in-situ metrology, close-loop control, and low-to-no support structures. One of the areas it is working on, alongside companies such as Materialise, is enabling a more personalized approach to patient care. Materialise’s Mimics inPrint software has been cleared to 3D print anatomical models for diagnostic use, giving hospitals a solution that is compliant with FDA regulations, with Stratasys printers validated for the manufacturing of the models. Stratasys was an early investor in Desktop Metal and the two companies have a strategic partnership that entails Stratasys' distributors selling the start-up's products. |
| **Voxeljet** | Hardware<br>Materials<br>Services | Germany | Voxeljet's roots go back to 1995 with the first successful dosing of ultraviolet resins. As part of a hidden project, initial 3D printing tests were performed at the Technical University of Munich. The company was subsequently established with the goal of developing new generative processes for the production of casting and plastics components using 3D printing. Its first orders, for the delivery of sand-based printers, came from car firms BMW and Daimler. It went public in the US in 2013. In May 2019, Voxeljet opened a new 78,000 square foot facility in Suzhou, near Shanghai, equipped with various large format and high-performance 3D printing systems and 400 tons of annual 3D printing capacity. In addition, the hub holds space for further 3D printer installations to meet the growing demand for 3D printed parts in Asia. |

Source: Company data, GlobalData

## Private companies

The table below lists some of the interesting private companies associated with this theme and summarizes their competitive position in the theme.

| Company | Segment | Country | Competitive position in the 3D Printing theme |
|---|---|---|---|
| **Aleph Objects** | Hardware<br>Software | US | Aleph Objects follows a principle of Libre Innovation, meaning its hardware and software is free to be copied, modified, and converted by users. It manufactures the LulzBot line of rapid prototyping 3D printers. The company has opened up European headquarters in Rotterdam and, in June 2019, announced a collaboration with FluidForm to design and produce new 3D bioprinting hardware as the company moves more into the professional, industrial, and biological arenas. FluidForm's Fresh printing technique was developed in Carnegie Mellon University's Regenerative Biomaterials and Therapeutics Group and enables 3D printing of bioinks and other soft materials. Together, Aleph Objects and FluidForm plan to work together on new bioprinting solutions, with the first offering expected in summer 2019. |
| **Apis Cor** | Hardware | US | Apis Cor is the first company to develop specialized equipment for 3D printing in construction that is capable of printing whole buildings completely on site. The company operates under the slogan "We Print Buildings", though only the walls of buildings are actually printed, because the 3D printer cannot yet participate in other processes. The company's partners include Gerdau, one of the largest suppliers of long steel in the Americas, SEArch (Space Exploration Architecture), which develops human-supporting design concepts for space exploration, and Autodesk. Working together, Apis Cor and SEArch won first place in the Phase 3: Level 3 element of NASA's 3D-Printed Habitat Challenge, a competition to create sustainable shelters suitable for the Moon, Mars, or beyond, using resources available onsite in these locations. The challenge puts teams to the test in several areas of 3D-printing, including modeling software, material development, and construction. |
| **Carbon** | Hardware<br>Software<br>Materials | US | 3D printing start-up Carbon has pioneered a process called CLIP – Continuous Liquid Interface Production (CLIP) – which, it says, combines engineering-grade materials with exceptional resolution and surface finish. CLIP is a photochemical process that eliminates the shortcomings of conventional 3D printing by harnessing light and oxygen to produce objects from a pool of resin ranging from tennis shoes and electronics to industrial components and highly customizable medical devices. It works by projecting light through an oxygen-permeable window into a reservoir of UV-curable resin. As a sequence of UV images are projected, the part solidifies and the build platform rises. Carbon argues that traditional additive approaches to photopolymerization typically produce weak, brittle parts. The company says it overcomes this by embedding a second heat-activated programmable chemistry in its materials, which results in high-resolution parts with engineering-grade mechanical properties. The company is partnering with Riddell, which makes (American) football helmets, to bring customized 3D printing and design to head protection for the US National Football League (NFL). Riddell helmets will feature a 3D printed lattice liner digitally manufactured using Carbon's Digital Light Synthesis technology. The result will be a customized, 3D printed helmet liner contoured to the athlete's head. |

| Company | Segment | Country | Competitive position in the 3D Printing theme |
|---|---|---|---|
| **Desktop Metal** | Hardware<br>Materials<br>Software | US | Two years ago, Massachusetts-based Desktop Metal launched two new systems covering the full product lifecycle, from prototyping to mass production. It argued that the systems – DM Studio and DM Production – change the game of traditional metal manufacturing solutions by reducing costs but increasing speed, safety, and print quality. The Studio System eliminates lasers and loose powders associated with metal 3D printing, making it safe, in Desktop Metal's view, to use in any facility, including an office environment. The Studio System printer uses bound metal deposition, an extrusion-based print technology that combines the powder metallurgy process of metal injection molding with the most widely used plastic 3D printing method, FFF. The Production System also uses single pass jetting technology which the company claims delivers speeds more than 100 times faster than quad-laser metal printers and over four times faster than the closest binder jetting alternative. Stratasys is an early investor in Desktop Metal. |
| **EOS** | Hardware<br>Materials<br>Software<br>Services | Germany | Founded in 1989 with a vision of going straight from CAD to manufacturing without tooling for the fabrication of physical components, EOS's first client was looking for a stereolithography machine (a type of resin-based 3D printer). 30 years on, EOS has now sold nearly 3,500 industrial 3D printing systems. In February 2019, it acquired Vulcan Labs to help expand its bench of AM experts in powder bed fusion technology. It is an example of 'acqui-hiring' in the 3D printing industry. EOS also specializes in materials for 3D printing and recently introduced four new materials. |
| **EnvisionTEC** | Hardware<br>Materials | US | EnvisionTEC now sells more than 40 printers based on six distinct technologies that build objects from digital design files. They are: digital light processing (DLP), where a vat of liquid photopolymer or resin is cured by a digital light source to build parts; continuous DLP, which offers an improvement on the DLP process that relies on continuous motion of the build plate to provide exceptionally fast builds; scan, spin, and selectively photocure (3SP) technology, where a laser uses a rapidly spinning mirror to selectively cure liquid resin into parts; bioprinting technology, in which the processing of biomaterials using pressure to a syringe can create scaffolds using a variety of materials; selective laminate composite object manufacturing, which processes a wide range of woven fibers pre-impregnated with thermoplastics using an ultrasonic cutting blade; and robotic AM technology, whereby a print head attached to an ABB robot arm uses an exclusive binder jetting technology to print sand molds and cores for the foundry industry. |
| **Formlabs** | Hardware<br>Software<br>Materials<br>Services | US | In 2019, Formlabs announced the addition of two new advanced professional low force stereolithography (LFS) 3D printers – the Form 3 and Form 3L- to its hardware lineup. The LFS process uses a flexible tank to significantly reduce the forces of the peel process, providing improved surface finish and detail, and linear illumination to deliver more accurate, repeatable parts. In addition to the new hardware, Formlabs also announced a new material, Draft Resin, which prints at 300 microns layer lines and is up to four times faster than other standard resins, making it ideal for rapid prototyping. One of Formlabs' partners is shaving tools specialist Gillette, with whom it has worked to create a series of customizable 3D printed handles, with a goal of matching advanced manufacturing with consumers' desire to have unique and personalized products. |

| Company | Segment | Country | Competitive position in the 3D Printing theme |
|---|---|---|---|
| **Markforged** | Hardware<br>Software<br>Materials | US | Markforged is a manufacturer of industrial 3D printers, print systems, and software. It operates at the high end of the 3D printing spectrum, focusing on more expensive 3D printers for industrial use cases. It typically manufactures parts in strong materials, such as carbon fiber, Kevlar, or stainless steel. In 2019, the firm opened European headquarters in Dublin and also raised $82m in a funding round led by Summit Partners. Markforged claims to have 10,000 customers, including Canon, Microsoft, Google, Amazon, General Motors, Volkswagen, Adidas, and in the UK, Dunlop. It shipped 2,500 printers in 2018. Both Markforged and its rival Desktop Metal have had legal battles over each other's' proprietary metal printing technologies, which are likely to continue. |
| **Nanoscribe** | Hardware<br>Materials | Germany | Nanoscribe, a spin-off of the Karlsruhe Institute of Technology, specializes in microfabrication and 3D printing using two-photon polymerization technology. Its technology is being used in sectors such as micro-optics, micromechanics, biomedical engineering, and photonics. In the field of micro-optics, the company suggests that nearly any three-dimensional shape with optically smooth surfaces can be materialized with its high-resolution 3D printers, circumventing limitations imposed by mechanical tools and geometrical or process design constraints common to subtractive techniques. Single micro-lenses, freeform optics, and compound lens systems can be printed without the need for post-print assembly of individual components. |
| **Optomec** | Hardware<br>Software<br>Materials<br>Services | US | Late in 2018, Optomec acquired Huffman, a specialist in supplying 3D metal printing systems for the additive repair of gas turbine components in the energy and aviation markets. Huffman's equipment and software are used by most major manufacturers of aircraft engines and industrial gas turbines, as its metal deposition capabilities can restore worn or damaged components at substantially lower cost than newly-made spare parts. Both Optomec and Huffman deliver a form of metal 3D printing known as directed energy deposition metal 3D printing. Optomec calls it LENS and argues it offers advantages over powder bed fusion or selective laser melting. It suggests LENS is able to add metal to existing parts for repair and coating applications that extend the useful life of components. |
| **Prusa 3D** | Hardware<br>Software<br>Materials | Czech Republic | Founded in 2012 in Prague as a one-man start-up offering an open-source solution, Prusa Research now employs over 400 people and, by the end of June 2019, had shipped over 130,000 machines. Prusa 3D espouses the upgradeability of its printers. The Original Prusa i3 can be upgraded to an Original Prusa i3 Plus 1.75mm (MK1) machine or to the latest printer, the Original Prusa I3 MK3S. |
| **Sculpteo** | Services<br>Materials<br>Software | France | Sculpteo is a prime example of an on-demand service provider for on-demand professional online 3D printing and laser cutting services for the production of prototypes, individual products, and short-run manufacturing. The company recently obtained the ISO 9001-2015 quality management standard which Sculpteo believes will enable it to partner with some of the largest industrial companies and also adapt to the requirements of cutting-edge sectors such as rail transport. |

| Company | Segment | Country | Competitive position in the 3D Printing theme |
|---|---|---|---|
| **Shapeways** | Services | US | Founded in 2007, Shapeways began as a spin-out of the lifestyle incubator of Royal Philips Electronics, and its investors now include Union Square Ventures, Lux Capital, and Presidio Ventures. Now headquartered in New York, Shapeways has a network of over 1 million businesses and has printed over 10 million products from its own factories and global supply chain network in over 50 materials and finishes. Shapeways is used in the manufacture of medical, devices, robots, drones, and other consumer products. |
| **Ultimaker** | Hardware<br>Software<br>Materials | Netherlands | Ultimaker is regarded as the market leader in desktop 3D printing. At the time of writing there are 125,000 Ultimaker 3D printers in use, compared to approximately 67,000 units in 2017. Ultimaker Cura, the company's open source software, has 500,000 unique users per month, up 100% in one year, and the company says it processes 1.4 million print jobs per week. Ultimaker recently announced that Heineken is using its solutions to produce a variety of custom tools and functional machine parts at its brewery in Seville. Using a set of Ultimaker S5 printers, engineers at Heineken now design and print safety devices, tools, and parts on-demand rather than outsourcing the job to external vendors, increasing production uptime and saving around 80% in production costs on the parts they 3D print. Ultimaker is also supplying Airbus with 3D printers, Cura software, and materials to use in its European facilities. |
| **XYZprinting** | Hardware<br>Software<br>Materials | Taiwan | In 2019, Taiwanese 3D printer manufacturer XYZprinting announced the launch of a new bundle program for teachers and schools, where a free 3D printer will be delivered alongside purchases of its K-12 STEAM curriculum. The bundle program is part of a bid from XYZprinting to facilitate the use of 3D printers in the classroom, investing in and encouraging the educational market to purchase its 3D printing STEAM curriculum. In May 2019, the company introduced its latest industrial stereolithography 3D printers and the first full-color industrial-sized fused filament fabrication (FFF) printer. |
| **Zortrax** | Hardware<br>Materials | Poland | Zortrax is a Polish developer of 3D printing solutions. Its main focus is in desktop 3D printers, while also offering dedicated filaments, software and additional devices to improve the printing process and post-processing. Late in 2018, Zortrax launched the M300 Plus, a new large build volume Wi-Fi 3D printer working in FFF technology, an original take on the FDM process. The additions of a Wi-Fi module and an Ethernet port to the printer allow for the creation of 3D printing farms. |

Source: Company data, GlobalData

# Who's Who in 3D Printing

In this section we identify the key players in the 3D printing industry and classify them by the markets they operate in and by the technology they utilize.

## Classification by value chain segment

The chart below details the key companies in the 3D printing industry and which segments of the 3D printing value chain they operate in: hardware, materials, software or services. Some companies operate across all four segments.

**Who's who in 3D printing: value chain**

Which parts of the value chain do they operate in?

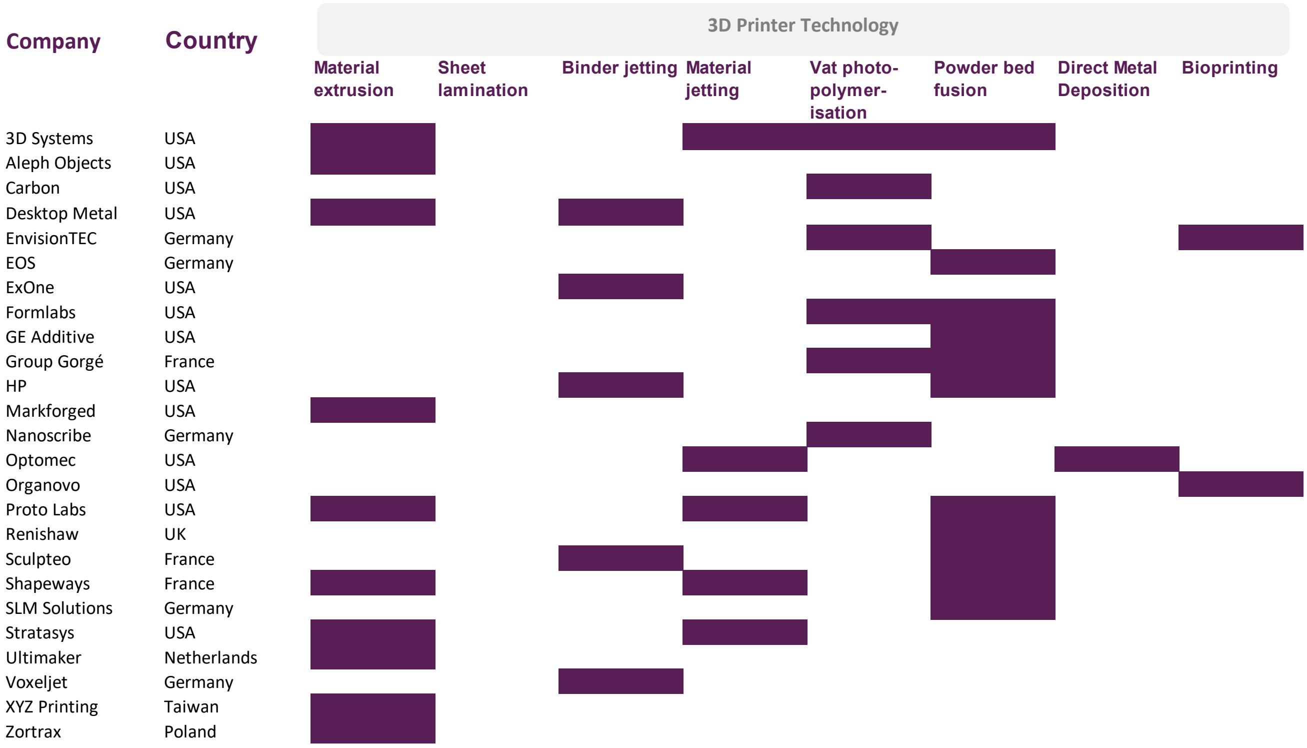

Source: GlobalData

## Classification by 3D printing technology

The chart below lists the key manufacturers of 3D printing hardware, classified by technology type.

**Who's who in 3D printing: hardware**

What type of 3D printers do they manufacture?




Source: GlobalData

# Glossary

| Term | Definition |
|---|---|
| **3D printing** | Also known as additive manufacturing, it refers to the process of joining materials to make objects from three-dimensional model data, usually layer upon layer. |
| **4D printing** | The process whereby a 3D printed object transforms its shape or behavior in response to an external stimulus, such as time, heat, moisture or sound. |
| **Anisotropic** | The state of having different values of properties in different directions. |
| **Artificial intelligence (AI)** | Refers to software-based systems that use data inputs to make decisions on their own. |
| **Atomization** | The process of dividing something (e.g. metal melt) into fine particles. |
| **Binder jetting** | A 3D printing technology that uses a powder as the build material but instead of fusing the powder with heat, it binds the powder together using a liquid bonding agent. Binder jetting is also known as inkjet powder printing. |
| **Bioink** | Bioprintable materials used in 3D bioprinting processes, where cells and other biologics are deposited in a spatially controlled pattern to fabricate living tissues and organs. Bioink can be composed simply of cells, but normally an additional carrier material that envelops the cells is added. |
| **Bioprinting** | A branch of 3D printing dedicated to the creation of living, organic cells by 'printing' them one layer at a time. |
| **Computer aided design (CAD)** | The use of computer software to aid in the generation, modification, analysis, or optimization of a design. |
| **Computer numerical control (CNC) machining** | A manufacturing process in which pre-programmed computer software dictates the movement of factory tools and machinery. The process can be used to control a range of complex machinery, from grinders and lathes to mills and routers. CNC machining (and injection molding) are complementary manufacturing processes to 3D printing. |
| **Cross-linked** | A bond, linking one polymer chain to another. |
| **Desktop systems** | Typically there are two main classes of 3D printer: desktop, and large-format. Desktop systems have previously been associated with the consumer but they are now increasingly making an impact on an industrial scale. Desktop printers can range from a budget $300 to $6000 depending on functionality. |
| **Diffusion** | The movement of atoms from one region to another. |
| **Digital twins** | Software representations of assets and processes that are used to understand, predict, and optimize performance in order to achieve improved business outcomes. Digital twins typically consist of three components: a data model, a set of analytics or algorithms, and knowledge. |
| **Direct metal deposition (DMD)** | One of the more expensive 3D printing technologies. It uses thermal energy to fuse build materials together by melting the material as is it being deposited, typically using a laser as an energy source. The technique introduces the build material as and when required. DMD is also known as directed energy deposition or laser-engineered net shaping. |
| **Direct metal laser sintering (DMLS)** | A 3D printing process similar to the laser sintering of polymer powders, known as SLS, but DMLS works with a variety of metal powders. A laser is slowly and steadily moved across the object surface to sinter the powder, which means that the particles inside the metal are fused together. |
| **Fatigue life** | The number of loading cycles that can be withstood before the material fails in the specified manner. |
| **Flowability** | The ability of a material to move by flow. |

| Term | Definition |
|---|---|
| **Fracture** | The process of atoms being separated. Fracture is the, often catastrophic, failure of a material. |
| **Hot isotatic pressing** | The part being treated is held in a high pressure, high temperature vessel for the required period of time, reducing porosity, leading to increased density and improved mechanical properties. |
| **Industrial Internet** | Refers to the use of connected sensors and actuators to control and monitor the industrial machinery environment, to help detect faults early and predict maintenance requirements. The Industrial Internet generally refers to heavy industries in which machine assets are connected to the internet. It typically comprises the following sectors: manufacturing, mining, construction and engineering, agriculture, utilities, and energy. |
| **Injection molding** | An important process for the mass production of objects. A thermoplastic polymer is heated above its melting point, which results in the conversion of a solid polymer into a viscous melt. The melt is then forced into a closed mold that defines the shape of the article to be produced. The material is then cooled until it becomes a solid. |
| **Internet of Things (IoT)** | Describes the use of connected sensors and actuators to control and monitor the environment, the things that move within it, and the people that act within it. |
| **Material extrusion** | The simplest, cheapest and most popular 3D printing technology. It uses a continuous filament of thermoplastic or composite material to construct 3D parts. The material, in the form of plastic filament, is fed through an extruding nozzle, where it is heated and then deposited onto the build platform layer by layer. Material extrusion is also known as fused deposition modelling (FDM) or fused filament fabrication (FFF). |
| **Material jetting** | A 3D printing process in which droplets of liquid build material are dispensed selectively by inkjet-printing heads as they move across the build area. Materials used in this process include photopolymers, which are hardened by visible light, or wax-like materials, which solidify as they are deposited. Material jetting is also sometimes referred to as multi-jet modelling and drop on demand (DOD). |
| **Milling** | A mechanical process where a rotating tool is used to cut/shape a material. |
| **Plastic** | A plastic is a polymer that has been modified with additives, and which can be molded or shaped under relevant conditions of pressure and temperature. Plastics are comprised of a long chain of polymers, where polymers are composed of smaller, uniform molecules. |
| **Polymer** | A chemical compound that contains a large number of identical molecular repeating units. |
| **Porosity** | A measure of the volume fraction of the voids in a material, compared to bulk material. Porosity is the volume of voids divided by the total material volume. |
| **Powder bed fusion** | A 3D printing process that uses a ‘pool’ of fine metal or polymer powder as its build material. An energy source – such as a laser or electron beam - supplies intense heat to specific localized spots and melts or sinters the powder together to form a 3D object. Powder bed fusion comprises several techniques, including selective laser sintering (SLS), direct metal laser sintering (DMLS), selective laser melting (SLM) or electron beam melting (EBM), multi-jet fusion, and direct laser microfusion (DLM). |
| **Radicals** | Charged atoms or molecules (unpaired valence electron is present). Unpaired valence electron means that the atom does not have a full out shell of electrons, so is charged (i.e. an ion). This makes it more reactive. |
| **Rapid prototyping** | A series of techniques used to quickly fabricate a scale model of a part or assembly. A 3D printer can deliver a full scale prototype in days instead of the weeks that might be taken with traditional methods. |

| Term | Definition |
|---|---|
| **Selective laser sintering** | A 3D printing technique in the ‘powder bed fusion’ category of methods which uses thermal energy to selectively fuse regions of a powder bed. Selective laser sintering uses a carbon dioxide laser and a thermoplastic polymer powder to ‘print’ parts. |
| **Sheet lamination** | One of the simplest 3D printing techniques, which uses paper, metal tape or foil bonded together using an adhesive to form a three dimensional object. Sheet lamination is also referred to as laminated object manufacturing (LOM) and ultrasonic additive manufacturing. |
| **Sintering** | A heating process which decreases porosity by giving atoms enough thermal energy to diffuse into voids, thus filling them. |
| **Standard Triangle Language (STL)** | A file format native to stereolithography CAD software created by 3D Systems. |
| **Subtractive manufacturing** | The process by which 3D objects are constructed by successively cutting material away from a solid block of material. Subtractive manufacturing can be done by manually cutting the material but is most typically done with a CNC machine. Subtractive manufacturing is the opposite to additive manufacturing (3D printing) in which a 3D object is constructed by successively depositing material in layers to achieve a predesigned shape. |
| **VAT photo-polymerization** | The original 3D printing technology. It solidifies layers of ultraviolet light-sensitive liquid polymer using laser technology. VAT photopolymerization is also known as stereolithography and digital light processing. |

Source: GlobalData

# Appendix: Our thematic research methodology

Companies that invest in the right themes become success stories. Those that miss the important themes in their industry end up as failures.

## Viewing the world's data by themes makes it easier to make important decisions

GlobalData's thematic research ecosystem is a single, integrated global research platform that provides an easy-to-use framework for tracking all themes across all companies in all sectors. It has a proven track record of identifying the important themes early, enabling companies to make the right investments ahead of the competition, and secure that all-important competitive advantage.

## Traditional research does a poor job of picking winners and losers

The difficulty in picking tomorrow's winners and losers in any industry arises from the sheer number of technology cycles – and other themes – that are in full swing right now. Companies are impacted by multiple themes that frequently conflict with one another. What is needed is an effective methodology that reflects, understands and reconciles these conflicts.

## That is why we developed our "thematic engine"

At GlobalData, we have developed a unique thematic methodology for ranking technology, media and telecom (TMT) companies based on their relative strength in the big investment themes that are impacting their industries. Our thematic engine identifies which companies are best placed to succeed in a future filled with multiple disruptive threats.

To do this, we rate the performance of the top 600 TMT companies against the 50 most important themes impacting those companies, generating 30,000 thematic scores. The algorithms in GlobalData's thematic engine help to identify the longer-term winners and losers within the TMT sector.

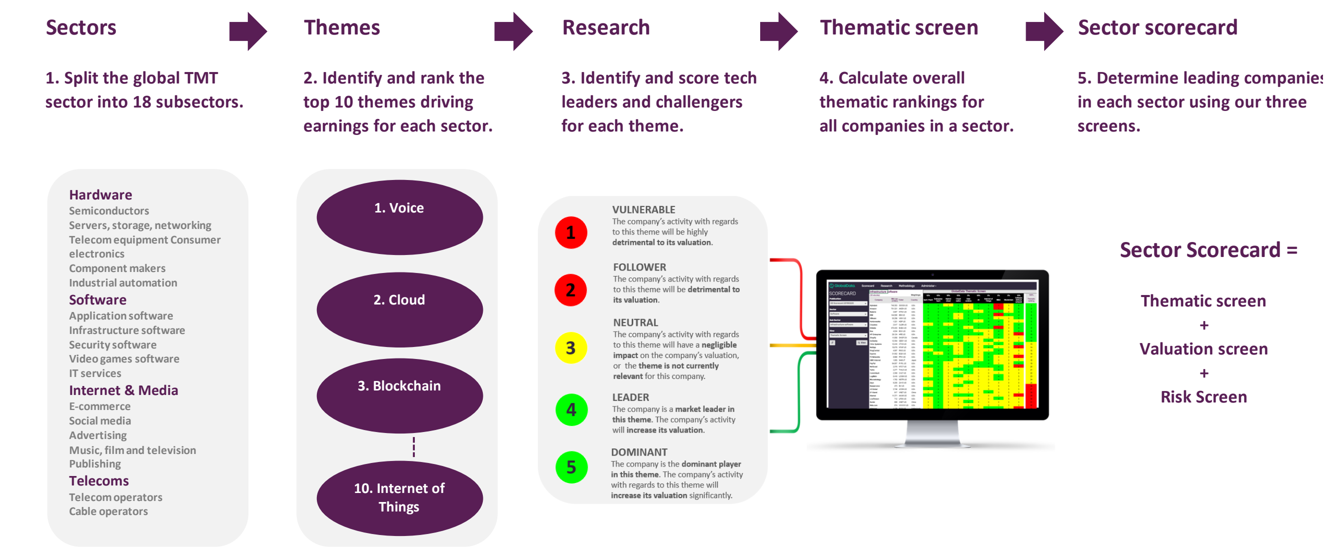
## How do we create our sector scorecards?

First, we split the global TMT industry into 15 sectors. Second, we identify and rank the top 10 themes for each sector (these can be technology themes, macroeconomic themes or regulatory themes). Third, we publish in-depth research on specific themes, identifying the winners and losers. The problem is that companies are exposed to multiple investment themes and the relative importance of specific themes can fluctuate.

So, our fourth step is to create a thematic screen for each sector to calculate overall leadership rankings after taking account of all themes impacting that sector.

Finally, to give a crystal clear picture, we combine this thematic screen with valuation and risk screens to generate a sector scorecard used to help assess overall winners and losers.

**Our five-step approach for generating a sector scorecard**




Source: GlobalData

## What is in our sector scorecards?

Our sector scorecards help us determine which companies are best positioned for a future filled with disruptive threats. Each sector scorecard has three screens:

- **The thematic screen** tells us who are the overall technology leaders in the 10 themes that matter most, based on our thematic engine;
- **The valuation screen** tells us whether publicly listed players appear cheap or expensive relative to their peers, based on consensus forecasts from investment analysts; and
- **The risk screen** tells us who the riskiest players in each industry are, based on our assessment of four risk categories: corporate governance risk, accounting risk, technology risk and political risk.

## How do we score companies in our thematic screen?

Our thematic screen ranks companies within a sector on the basis of overall technology leadership in the 10 themes that matter most to their industry, generating a leading indicator of future earnings growth.

Thematic scores predict the future, not the past.

Our thematic scores are based on our analysts' assessment of their competitive position in relation to a theme, on a scale of 1 to 5:

1. **Vulnerable:** The company's activity with regards to this theme will be highly detrimental to its future performance.
2. **Follower:** The company's activity with regards to this theme will be detrimental to its future performance.
3. **Neutral:** The company's activity with regards to this theme will have a negligible impact on the company's future performance, or this theme is not currently relevant for this company.
4. **Leader:** The company is a market leader in this theme. The company's activity with regards to this theme will improve its future performance.
5. **Dominant:** The company is a dominant player in this theme. The company's activity with regards to this theme will significantly improve its future performance.

## How our research reports fit into our overall thematic research ecosystem

Our thematic research ecosystem is designed to assess the impact of all major themes on the leading companies in the TMT sector. To do this, we produce three tiers of thematic reports:

- **Single Theme:** These reports offer in-depth research into a specific theme (e.g. artificial intelligence). They identify winners and losers based on technology leadership, market position and other factors.
- **Multi-Theme:** These reports cover all companies and all themes within the TMT sector. There are two types: one is organized by sector; the other is organized by theme.
- **Sector Scorecard:** These reports identify those companies most likely to succeed in a world filled with disruptive threats. They incorporate our thematic screen to show how conflicting themes interact with one another, as a well as our valuation and risk screens.

# About GlobalData

4,000 of the world's largest companies make better and more timely decisions thanks to our unique data, expert analysis and innovative solutions delivered through a single platform.

GlobalData is one of the world's leading providers of company operational data and strategic analysis, providing detailed information on tens of thousands of companies globally. Our highly qualified team of Analysts, Researchers, and Solution Consultants use proprietary data sources and various tools and techniques to gather, analyze and represent the latest and the most reliable information essential for businesses to sustain a competitive edge. Data is continuously updated and revised by large teams of research experts, so that it always reflects the latest events and information. With a large dedicated research and analysis capability, GlobalData employs rigorous primary and secondary research techniques in developing unique data sets and research material for this series and its other reports. GlobalData offers comprehensive geographic coverage across world's most important sectors, focusing particularly on energy and healthcare.

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## Disclaimer