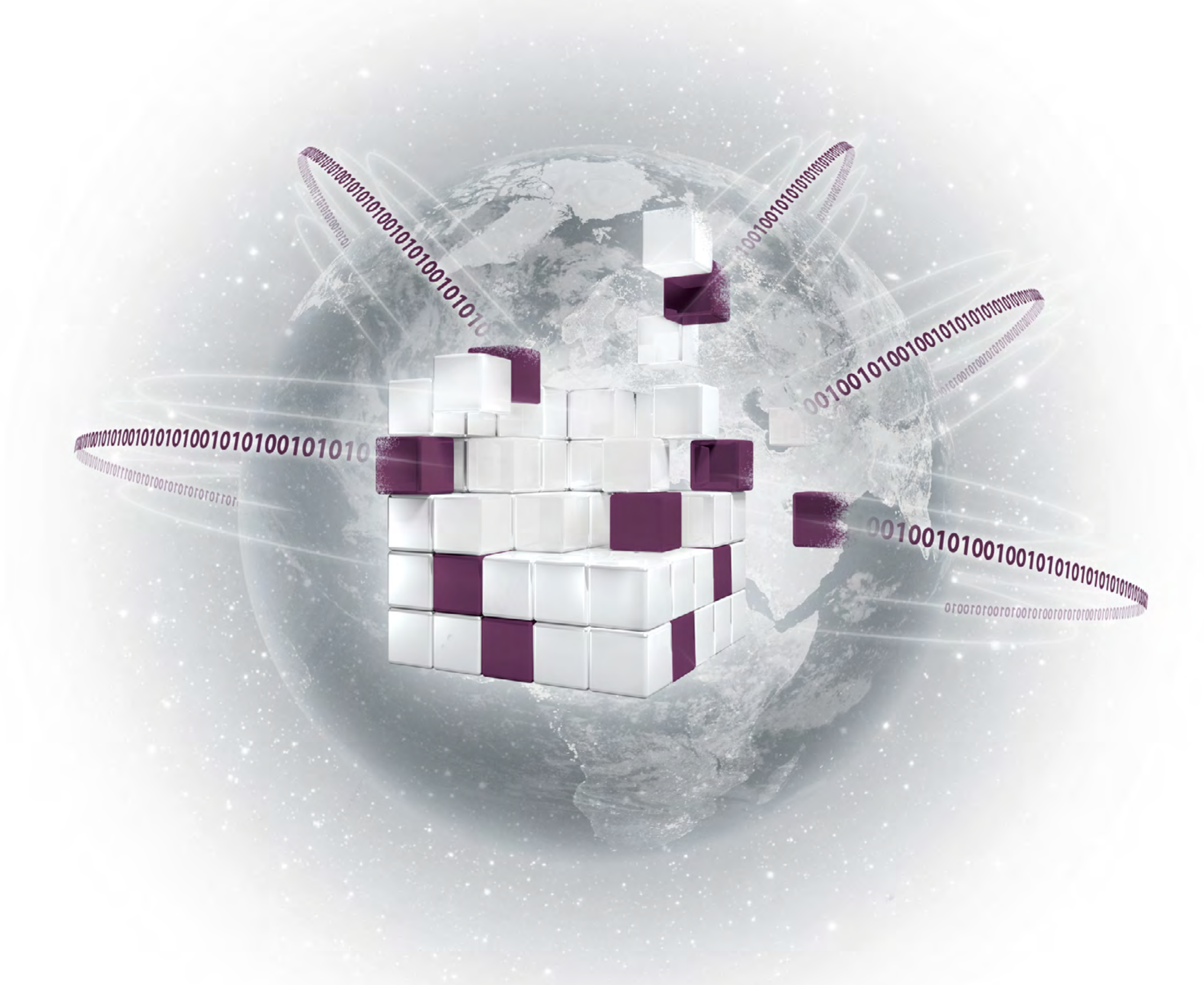

# 3D PRINTING AND THE FUTURE OF SUPPLY CHAINS

## A DHL perspective on the state of 3D printing and implications for logistics

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# PREFACE

Science fiction is fast becoming science fact as 3D printing begins to make inroads into manufacturing, from product design right through to the production floor. From engineering to automotive to healthcare, companies are recognizing that 3D printing presents an opportunity to 'do things differently'. It allows us to profoundly rethink the way we create and manufacture products, as well as fundamentally reassess the design of supply chains.

In our Logistics Trend Radar, we identified 3D printing as one of the major disruptive trends to impact the logistics industry in the near future. We believe this is due to the immense potential for 3D printing to create instant production and distribution models, essentially enabling companies and consumers alike to print complex objects within the confines of a single printer.

Of course, not all products and parts can and will be 3D printed. Therefore it will be essential to understand early on where 3D printing will be advantageous to your manufacturing and supply chain strategies. To support you in assessing the implications of 3D printing, this DHL trend report provides insights and answers to the following key questions:

- **What is the current state of 3D printing and how is this technology being applied?**
- **What competitive advantages can 3D printing offer to your organization?**
- **What are the crucial success factors for the widespread adoption of 3D printing?**
- **What are the opportunities for 3D printing in your future supply chain?**

Looking ahead, we anticipate change from 3D printing that is both broad and deep, specifically in areas of spare parts manufacturing, individualized parts manufacturing, and end-of-runway 3D printing services.

The dialog on 3D printing is building, and we hope you find this an enlightening read and look forward to discussing the exciting potential of 3D printing in your supply chain.

Yours sincerely,

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# 1 UNDERSTANDING 3D PRINTING

## 1.1 Introduction: Building the future with 3D printing

3D printing, otherwise known as "additive manufacturing", has been capturing the imagination of everyone from entrepreneurs to at-home hobbyists in recent years. Today, thanks to widespread media coverage of 3D printing, there is a growing surge in mainstream interest, with exciting new breakthroughs and applications being announced virtually every day (see figure 1).

In the enterprise, there is also growing hype and excitement that 3D printing can potentially revolutionize manufacturing, enabling companies to produce almost anything, layer by layer within the boundaries of a single 3D printer. Already today, leading companies eager to be first-mover winners in a 3D printing future have begun to leverage this technology, demonstrating inspiring applications across a range of industries, from aviation to healthcare and even food production.

By making big investments, some companies are already betting on the success of 3D printing for their businesses. Major moves in 2016 alone include the Mercedes-Benz Truck announcement of its first 3D-printed spare parts service, the launch of HP's 3D printing initiative, and a multimillion dollar investment by GE, BMW, and Nikon into the 3D printing start-up, Carbon[1], to name just a few.

While expectations and optimism for 3D printing continue to increase both in the consumer and enterprise contexts, the key questions remain: **Will 3D printing really disrupt global manufacturing? Will 3D printing render traditional manufacturing factories obsolete? And consequently, will logistics volumes be disrupted?**

The answers to these questions depend largely on changes in economics, new technological breakthroughs, and future levels of 3D printing adoption. At present, many leading industry and market analysts are making promising growth predictions for 3D printing. The consultancy firm McKinsey estimates that the 3D printing market will grow to between $180 billion and $490 billion by 2025.[2] Similarly, Gartner, the well-known information technology advisory company, believes that enterprise 3D printing is ready to break out and achieve widespread adoption.

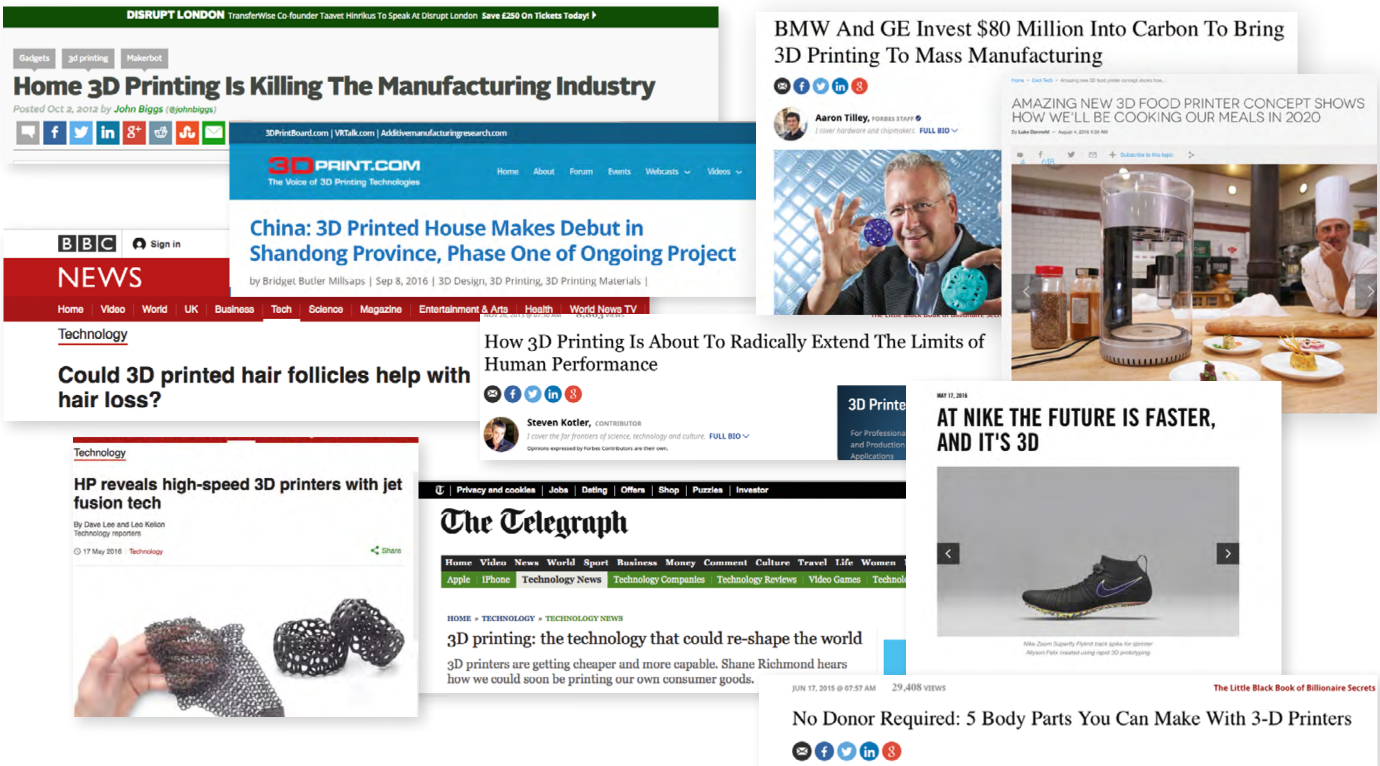


**Figure 1:** 3D printing – media hype or manufacturing reality?

1 http://fortune.com/2016/09/15/ge-bmw-nikon-carbon-3d-printing/
2 McKinsey

This is illustrated in Gartner's annual hype cycle of emerging technologies which shows the accelerating maturity of enterprise 3D printing (see figure 2). Over the past five years, enterprise 3D printing has successfully moved from being a nascent technology to reaching the cusp of the plateau of productivity, signaling that mainstream adoption is starting to take off. In contrast, consumer 3D printing is still at the peak of inflated expectations and will require more time before it reaches mass adoption.

This uptick in 3D printing investments and adoption can be attributed to the increasing number of companies beginning to realize, on the one hand, the possibility for new 3D printing business models and services and, on the other hand, the major economic advantages of 3D printing compared to conventional manufacturing techniques. With traditional manufacturing, materials are usually sourced and shipped from several locations to centralized factories that develop and assemble the final product.

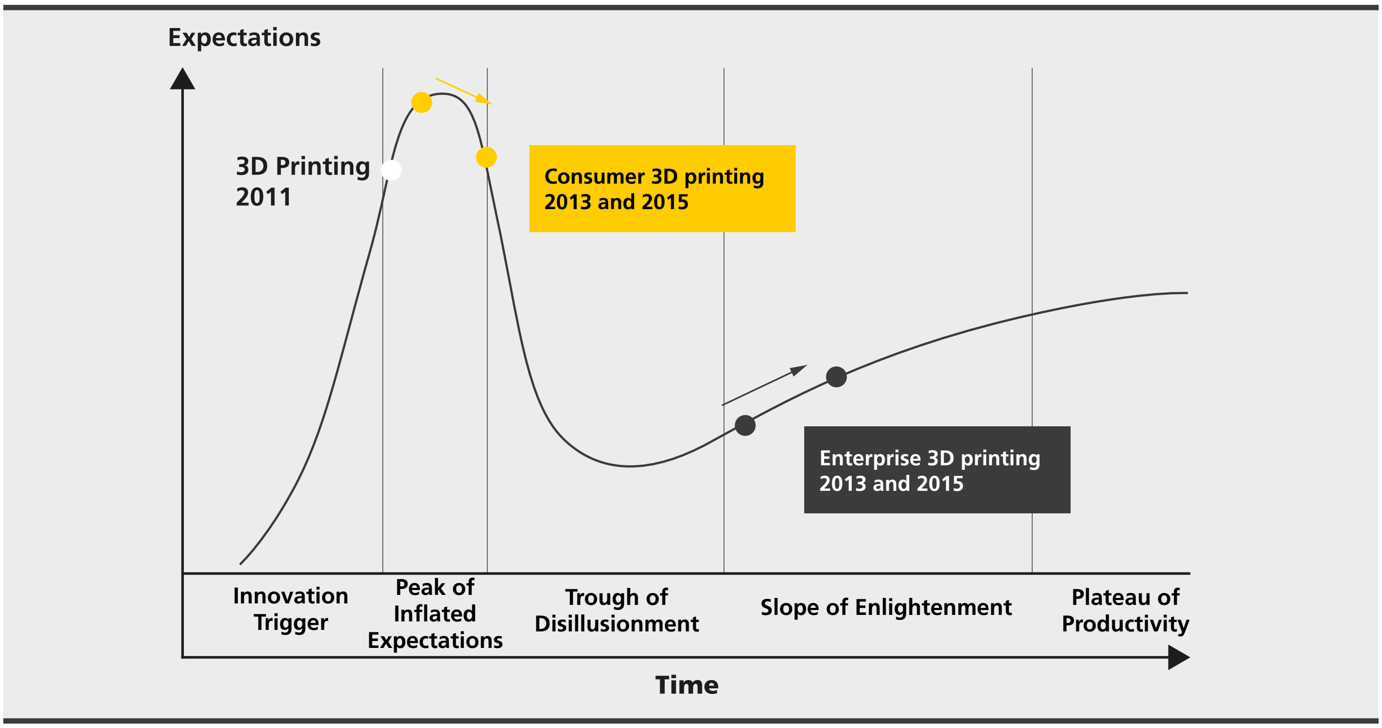


**Figure 2:** 3D printing in the Gartner Hype Cycle; **Sources:** Gartner (2011, 2013, 2015)

## Does 3D printing make sense? The economics of 3D printing

- Lower number of production steps to design, prototype and manufacture highly complex and/or customized products
- Faster delivery time through on-demand and decentralized production strategies
- Lower logistics and production costs (e.g., reduced shipping and storage costs, potential elimination of import/export costs through localized production, elimination of new production tools and molds and costly modifications to factories)
- Higher sustainability and efficiency in production through using the least amount of material and energy in production

**Figure 3:** Key advantages of 3D printing; **Source**: DHL

The finished goods then pass through several steps in the supply chain, usually being stored in warehouses before delivery to stores or directly to the end-customer once an order has been placed.

3D printing, in contrast, can greatly reduce complexity in manufacturing and holds a number of additional advantages over conventional production techniques (see figure 3). A major benefit of 3D printing is the ability to produce a variety of products from a single 3D printer. This reduces the number of steps in the production chain, essentially enabling companies to leverage on-demand and decentralized production concepts. As a result, potentially significant economic savings can be made on logistics and production costs.

Companies can also find additional savings from the reduction of production waste as well as the increase of sustainable business practices through 3D printing. A study by Airbus showed that by redesigning its brackets for 3D printing, the company could achieve a 40% reduction in $CO_2$ emissions over the lifecycle of the bracket and reduce the weight of the airplane by 10 kg. 3D printing also enabled a 25% reduction in material waste compared to traditional casting methods (see figure 4).[3]

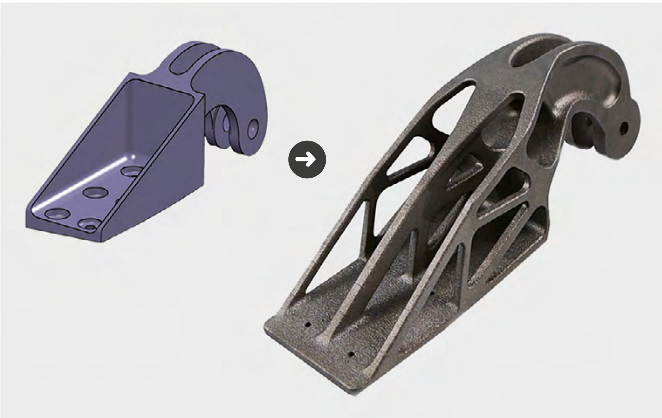

**Figure 4:** Left – a conventional bracket design. Right – a bracket optimized for 3D printing; **Source:** Eos

Taking these advantages into consideration, figure 5 illustrates some calculations on the economics of 3D printing for everyday household items that require some customization – for example, a shower head that needs to fit the size of the pipe or an iPad stand that needs to be designed to the model's exact size. For these customized printed objects, the potential savings are anywhere between eight to 80 times an equivalent retail price. Consumers and businesses can make substantial savings by 3D printing these objects themselves.

This shows that leveraging 3D printing in the right product segments makes sense. It can especially provide great value where there is a high level of complexity and customization in the design and production of a product as well as where there is a need for smaller batch sizes. Therefore it will be essential to understand where 3D printing will be advantageous compared to traditional manufacturing and supply chain strategies.

| ITEMS | RETAIL PRICE RANGE | COST TO 3D PRINT |
|---|---|---|
| Shower Head | $7.87 – $437.22 | $2.53 |
| Jewelry Organizer | $9.00 – $104.48 | $0.70 |
| iPad Stand | $82.84 – $812.85 | $10.69 |

**Figure 5:** The economics of 3D printing; **Source:** Joshua Pearce (2013)

## 1.2 How does 3D printing work?

Put simply, the functions of a classic 3D printer are quite similar to those of a conventional inkjet printer. Both obtain printing information from a digital file but, while inkjet printers apply ink to paper, 3D printers inject materials in successive patterns to build a three-dimensional solid object. This is also what differentiates 3D printing from conventional manufacturing methods: material is added layer by layer instead of molding or cutting or bending materials.

Three basic ingredients are essential for the 3D creation of an object:

1. **A digital model** – this is the digital design information needed to print an object. Digital models can be created from scratch using design programs such as CAD (computer-aided design) or by using a scanner to capture a 3D virtual image of an existing object. To enable the 3D printer to construct a physical object out of the virtual model, 3D modeling software "slices" the model into hundreds or thousands of horizontal layers, depending on the size and structure of the object.[4]

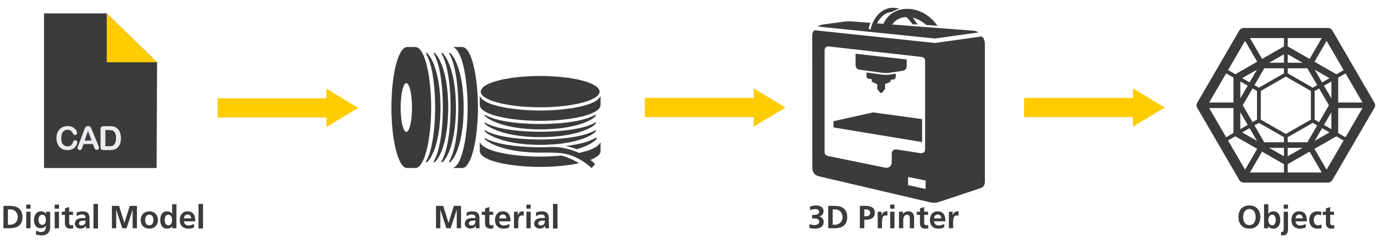


**Figure 6:** The 3D printing process; **Sources:** DHL, Flaticon.com

[3] http://www.eos.info/eos_airbusgroupinnovationteam_aerospace_sustainability_study
[4] http://3dprinting.com/what-is-3d-printing/

2. **Feed material** – this is the material that is used to ultimately manufacture the final object. Today it is estimated that 52% of companies demand metal as a precondition for widespread application of 3D printing, followed by polymers at 31%.[5] Besides these two materials, many companies are also successfully experimenting with other materials such as ceramics, concrete, and even food.

3. **A 3D printer** – this is the hardware used to create the solid object out of the digital model and feed material. 3D printers come in various forms utilizing different techniques to produce the object. Selection depends on whether the application is for consumer or enterprise purposes. Today, commercial 3D printers for industrial use can have price tags reaching the one million dollar mark; the cheapest pre-assembled consumer 3D printers cost under $400.[6]

## What are the different ways of 3D printing?

The term "3D printing" covers a range of printing technologies that apply different approaches. Today there are over ten different 3D printing technologies to choose from; however a 2016 survey of over 1,000 3D printing users revealed that mainly three technologies are used (see figure 7).[7] These are selective laser sintering, fused deposition modeling, and stereolithography.

- **Selective laser sintering (SLS)** uses lasers to melt powdered feed material into the desired object. It is most established in professional and industrial contexts as it also allows the printing of metal-based materials.

- **Fused deposition modeling (FDM)** is the most widely adopted and user-friendly 3D printing technology and the one that's most familiar to consumers. FDM printers use hardened feed material (usually plastic on a coil) which is then fed into the printer and melted layer by layer to produce the final object.

### TOP 3D PRINTING TECHNOLOGIES

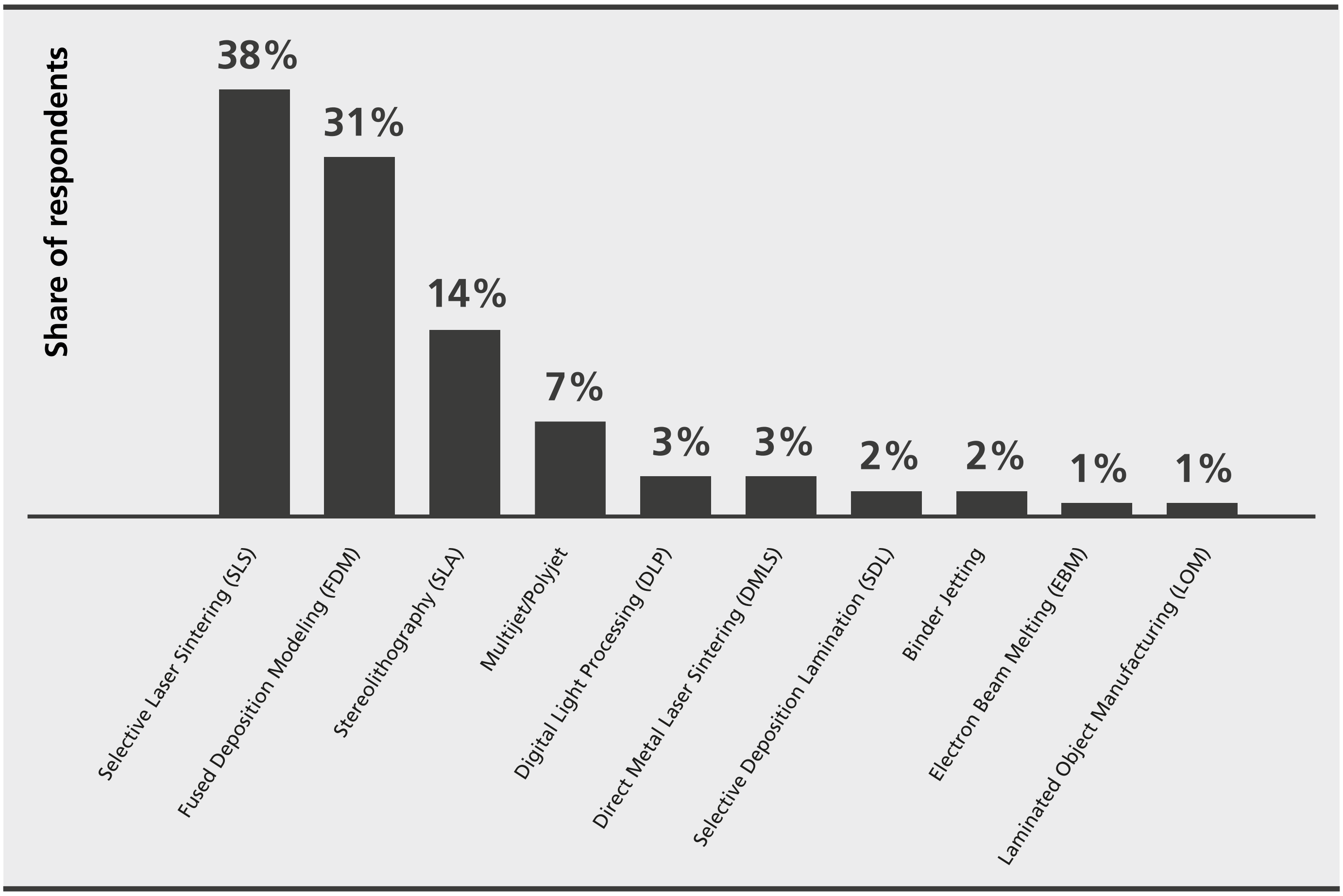


**Figure 7:** Top 3D printing technologies; **Source:** Sculpteo

[5] Ernst & Young's Global 3D Printing Report, 2016
[6] https://all3dp.com/best-cheap-budget-3d-printer-affordable-under-1000-budget/
[7] Global 3D Printing Report, Sculpteo 2016

- **Stereolithography (SLA)** uses a moving laser beam to build up the object, layer by layer, from a liquid polymer that hardens on contact with the laser's light. SLA is well established for rapid prototyping applications.

There has been a recent surge in innovation for these top three 3D printing technologies; however, the majority of this new activity especially in the consumer context has occurred with FDM printers. This can largely be attributed to the expiration in 2009 of a major patent on the FDM apparatus and method (held by its inventor since 1989). This has paved the way not only for more technological advancements and solutions, but also the development of a more competitive ecosystem.

## 1.3 Key success factors for widespread adoption of 3D printing

Despite the many benefits of using 3D printing for a variety of different product types, only a handful of early industry adopters have integrated it as a core production technology. The exception to this is the medical and healthcare industry; the creation of 3D-printed prosthetics and implants (such as hearing aids and dental crowns) is now common practice.

The limited scale of adoption is surprising considering the fact that 3D printing has been around since the 1980s. According to Ernst & Young's Global 3D Printing Report 2016, 11% of companies[8] in its survey are testing and experimenting with 3D printing, while just 3% claim significant experience of 3D printing and have a clear strategic plan at the highest management level for its future application.[9] Some reasons why adoption has been slow include lack of technological maturity for most industrial-grade applications, high costs for printers and materials, and limited knowledge about 3D printing technology.

Therefore, the widespread adoption of 3D printing will depend on the realization of five key success factors:

- Material technology
- Process speed and quality
- Warranty and liability issues
- Intellectual property challenges
- Printer, material, and scan costs

**Material technology** is a critical success factor for 3D printing. While there is a broad range of available materials for 3D printing, there remains the challenge of creating a single object from multiple materials. Printers are available on the market that can handle up to three different materials; however, costs are still prohibitively high and quality issues persist. Prototypes such as the MIT Computer Science and Artificial Intelligence Lab (CSAIL) MultiFab printer are testing the feasibility of using up to ten materials in a single print run.[10] Multi-material printing would play a pivotal role in expanding the range of printable products, especially for consumer 3D printing.

**Figure 8:** 3D printers need to handle a variety of materials; **Source:** Softpedia

[8] Different-sized companies from 12 countries out of 9 industries: Aerospace, Automotive, Consumer Goods, Electronics, Energy, Logistics and Transportation, Mechanical and Plant Engineering, Wholesale and Retail and other services
[9] Ernst & Young's Global 3D Printing Report, 2016
[10] http://cfg.mit.edu/content/multifab-machine-vision-assisted-platform-multi-material-3d-printing

**Figure 9:** Faster process speed and quality is essential; **Source:** Stratasys

The second success factor for 3D printing is **process speed and quality**. Today a typical consumer-grade FDM printer requires 4-5 hours to print a golf ball and approximately 9 hours to print a more complex object of the same size. But to achieve mainstream success, 3D printing must represent a much faster alternative to buying in store or ordering the same product online. In addition, the quality of each item – both in terms of aesthetics and structural integrity – must be maintained. New developments to tackle speed and quality challenges include HP's Multi Jet Fusion Technology as well as Carbon 3D's liquid 3D printing that offers 10 to 100 times faster print output without loss of print quality.[11,12]

**Figure 10:** What will the legal situation look like?; **Source:** Williams Pitt

Another major success factor will be establishing **warranty and liability frameworks** for 3D printing. What happens when a 3D-printed part breaks? Where does liability lie? In different cases, the responsibility could be with the user, the manufacturer of the 3D printer, the producer of the digital model, or the company that uses the 3D printer to deliver its services. The current regulatory framework remains underdeveloped; however, leading insurance companies such as Zurich are starting to scope product liability risks arising from 3D printing.[13] Insurance solutions will certainly play a significant role in allowing companies to shield against potential liability claims.

Companies that have traditionally competed using best-in-class production methods will have to deal effectively with **intellectual property challenges** when they begin to rely on 3D printers and the security of their digital files as corner-stones of their competitive advantage. If a company loses the protection of its files, third parties may be able to replicate its products. In the manufacturing sector, this could raise the same kinds of issues faced by media companies today with the pirating of digital music and video files.

**Figure 11:** A secure solution is required to protect intellectual property; **Source:** Bio-Nano

The fifth success factor for this trend will be 3D **printer, material, and scan costs**; lower prices will be critical to future mass adoption of 3D printing. Many advanced industrial 3D printers in the past were too costly for wide-spread usage; however, high-quality machines running on SLA technology are available today for a few thousand dollars (such as the Formlabs Form 2 which costs around $3,500[14]). Other consumer-grade printers such as the Ultimaker and MakerBot cost only a few hundred dollars, which gives promising indications that 3D printers will continue to become more and more affordable in the future.

[11] http://www8.hp.com/us/en/printers/3d-printers.html
[12] http://carbon3d.com/
[13] https://www.zurichna.com/en/knowledge/topics/3d-printing
[14] https://all3dp.com/best-sla-3d-printers/

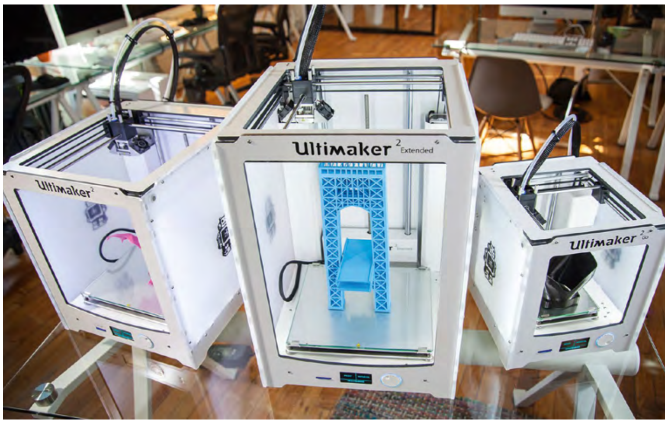


**Figure 12:** Lower 3D printing costs will be a key catalyst for widespread adoption; **Source:** Ultimaker

Between 2010 and 2016, the average price for 3D printers dropped by around 30%. Further decreases are expected at a rate of 6% annually till 2019.[15]

Besides the physical printers required for production, other aspects of cost are the materials and the creation of CAD files. 3D-printing materials are more expensive than buying just raw material, with the cheapest per kilogram being about $15 and ranging up to $1,200 for carbon fiber.[16] Scanning a complex object to convert it into a robust CAD file typically requires high-end scanning services which can cost from several hundred dollars to several thousand dollars and can take days to complete.

Through improvements in low-cost scanning technologies, it should be possible to scan objects using more affordable mobile devices. For example, the start-up Eora 3D has launched a very successful crowdfunding campaign to develop a low-cost, high-precision laser scanner that will be entirely powered via smartphone.[17]

In combination, when these five success factors are achieved, there will be widespread 3D printing adoption in both the consumer and enterprise contexts. And once these success factors are met, unique opportunities as well as challenges will be presented to the global supply chains that underpin today's manufacturing economies. In order to understand where and how 3D printing is currently being utilized, the next chapter explores best-practice examples from various industries.

**Figure 13:** Eora has developed a low-cost, high-precision laser scanner for iPhones; **Source:** Eora

[15] http://media.ibisworld.com/2016/02/16/innovation-in-creation-demand-rises-while-prices-drop-for-3d-printing-machines/
[16] https://all3dp.com/buy-3d-printing-filament/
[17] https://eora3d.com/

# 2 CURRENT APPLICATIONS FOR 3D PRINTING

In this chapter we present examples of how companies across many industries are already applying 3D printing and exploiting its advantages, from consumer 3D printing to industrial applications. These demonstrate what is already possible today with 3D printing, and provide an indication of how applications could be expanded in the future.

We also show how new business models might emerge and consider some important breakthrough 3D printing applications with disruptive potential. This exploration helps to gauge the disruptive impact of 3D printing and identify opportunities to leverage 3D printing in future supply chains.

## 2.1 Individualized production

### Consumer 3D printing: Not only gadgets and gimmicks

Consumer 3D printing applications have tended to focus on creating gadgets and gimmicks but today there's a wide variety of meaningful 3D printing applications. This can be attributed to the rise of the do-it-yourself culture which is blurring the distinction between producer and consumer, creating a new phenomenon of 'prosumerism'. 3D printing can support consumers to design and create their own products to meet their individual tastes and requirements.

One area where there is an abundance of activity in the use of 3D printing is educational development. 3D printing is being tested by many schools as well as in homes to rethink the way students engage and learn. To embrace the creativity of children, toy giant **Mattel** has partnered with Autodesk to launch **ThingMaker** which is currently retailing for $299.[18] The ThingMaker's Design App allows children to intuitively design toys that can be connected

**Figure 14:** Mattel`s ThingMaker; **Source:** Mattel

to create larger toys. The 3D models can be created on a tablet or smartphone and sent wirelessly to a 3D printer.

As well as creative 3D printing tools for children, more and more consumer 3D printing applications are becoming available. For example, consumers who want to differentiate themselves through fashion and jewelry can now use 3D printing to express creativity in a customized manner. One start-up that is providing this type of solution is **Normal Earphones**; the company prints custom-fit and custom-designed headphones for consumers by analyzing pictures of each individual's ears.

**Figure 15:** Customized 3D-printed earphones; **Source:** Cimquest

[18] http://www.thingmaker.com/design/

## Professional 3D printing for customized healthcare

3D printing is also being widely used in the area of professional individualized healthcare to improve patient experience and service quality. Makeshift prostheses reveal only a hint of what is possible with more advanced 3D printing equipment. Alongside this, new production processes are drastically changing industries from orthopedics to prosthetic dentistry. Comparable practices are being launched in orthodontics, specifically for dental prostheses. Laser scanners create a 3D model of a person's teeth and calculate an adequate model for a replacement item such as a dental crown.

**NextDent** is one 3D printing company that produces personalized dental crowns ensuring an accurate aesthetic and functional fit for the patient. This is done through a 3D scan of a tooth which is then 3D printed in resin.[19] Another example is **Renishaw**, a British engineering company that operates three 3D printing machines; each machine sinters in one batch 200 personalized dental crowns and bridges from a cobalt-chrome alloy, achieving faster, cheaper production than with ceramic counterparts. Dental laboratories from all over Europe can order from Renishaw's facility.[20]

**Figure 16:** Personalized dental crowns are already possible today; **Source:** NextDent

Another example is the start-up **SOLS** which delivers orthopedic insoles via two business models: Customers can scan their feet either with self-scan or via an orthopedist, and their completed 3D-printed soles are then sent directly to them. Similarly, companies like **Feetz** and **3DShoes.com** offer individualized sport shoes.[21] Customers scan their feet using a smartphone camera and select their desired shoe design, colors, and materials. They then receive a tailored pair of shoes three days later for between $50 and $180. **Adidas** and **Nike** are already testing a similar service in their stores.[22]

**Figure 17:** 3D printed shoe soles; **Source:** SOLS

**Robohand** is a further example of innovative individualized healthcare through 3D printing. This is a snap-together hand prosthetic that is adaptable to different hand sizes. The design is readily available for free on the Internet with a total cost of under $100 to produce a single Robohand. While this prosthesis may lack medical perfection, it is easily printable and can be used as an interim support until, for example, a more refined prosthesis is available.

Surgeons have also begun to successfully test the use of 3D-printed components inside the body. Surgeons in Bangkok recently successfully implanted a titanium implant inside a woman's hand. The bone prosthesis, which was printed by **Chualongkorn University** engineers, replaced a thumb bone that had been severely damaged.

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[19] http://nextdent.com/
[20] http://www.economist.com/news/science-and-technology/21697802-3d-printing-coming-age-manufacturing-technique-printed-smile
[21] http://www.sols.com/, http://www.3dshoes.com/collections/3d-printed-shoes
[22] http://www.adidas-group.com/de/medien/newsarchiv/pressemitteilungen/ 2015/massgeschneidert-aus-dem-3d-drucker-erschaffe-deinen-individuell/, http://news.nike.com/news/allyson-felix-track-spike

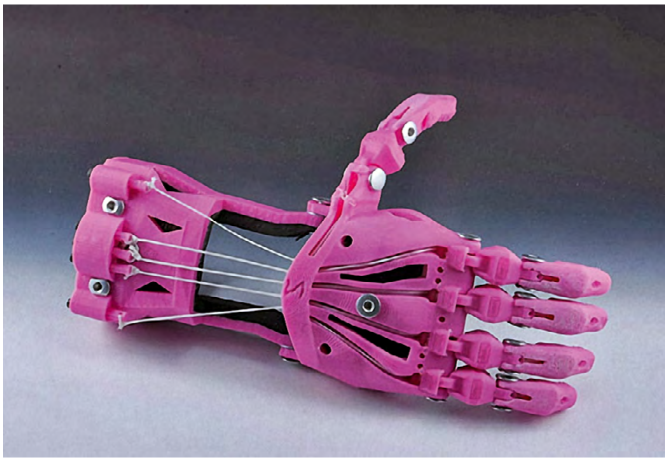

**Figure 18:** The snap-together hand prosthetic Robohand; **Source:** Rasterweb

These are only a few of many fascinating examples of individualized production using 3D printing. In healthcare especially, there's sure to be increasingly widespread use of 3D printing. In fact it is estimated that, by 2019, 3D printing will be a critical tool in individualized healthcare. By then, predictions suggest that 3D printing will be used in over 35% of all surgical procedures requiring prosthetic and implant devices in and around the body, and up to 10% of people in the developed world will be living with 3D-printed items on or in their bodies.[23]

## 2.2 Manufacturing complex products

Besides the use of 3D printing for highly tailored production to meet individual requirements, 3D printing can also be used to make very complex products. This means that 3D printing is likely to have significant impact in industries involved in heavy production such as automotive and manufacturing. By 2019, it is estimated that 10% of all discrete manufacturers will be using 3D printers to make parts for the products they sell or service. To illustrate some of the complex structures being 3D printed today, below are some key examples of current implementations of 3D printing in manufacturing industries.[24]

In the automotive sector, the start-up **Local Motors** already has a considerable track record of utilizing 3D printing technology to create vehicles. The company has designed the world's first 3D-printed electric car, called Strati. 75% of the car, from chassis to body, is 3D printed using carbon fiber-reinforced ABS plastic. Local Motors needed only two months from initial design to final production of the prototype, demonstrating how 3D printing technology can be leveraged to reduce time-to-market.

**Figure 19:** Local Motor's 3D-printed car; **Source:** Local Motors

Many established manufacturing companies have also successfully implemented 3D printing technology in their manufacturing processes, often achieving remarkable results. This is most evident in the aerospace and automotive industries. Pursing the evolution and use of advanced additive-manufacturing methods, the **BMW Group** has to date integrated 10,000 3D-printed parts into series production of the Rolls-Royce Phantom, claiming that new technologies like this will shorten production times and achieve more economical production in car manufacturing.

[23, 24] http://blogs.gartner.com/pete-basiliere/2015/12/02/gartner-predicts-2016-3d-printing-disrupts-healthcare-and-manufacturing/

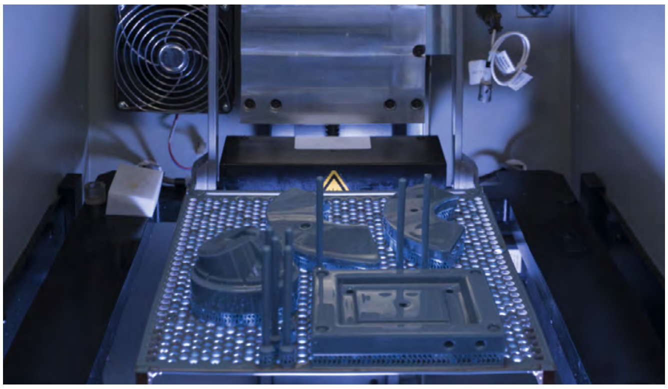

**Figure 20:** The Rolls-Royce Phantom has more than 10,000 3D printed parts; **Source:** 3D Print

**General Electric** recently opened its multi-modal manufacturing site, a massive additive-manufacturing facility that produces 3D-printed parts such as fuel nozzles for GE's advanced LEAP jet engines. GE has been using 3D printing for some time to rapidly manufacture replacement materials. Now it is moving to integrate 3D printing into its primary manufacturing processes. The new fuel nozzle design, enabled by 3D printing, is 25% lighter and five times more durable than the earlier model that was produced conventionally. The nozzle was previously made up of 20 parts, which had to be procured from various suppliers, and then assembled together. Now they can be manufactured in a single step.[25]

**Airbus** is utilizing 3D printing in the construction of its airplanes and has already introduced over 1,000 3D-printed parts in its latest A350 model.[26] Airbus is also experimenting with aircraft that are entirely 3D printed. At the 2016 International Aerospace Exhibition, it presented Thor – a completely 3D-printed drone consisting of 50 3D-printed parts and two electric motors. This aircraft, which is 4 m long and weighs 21 kg, was constructed in just 4 weeks.[27]

## 2.3 Decentralized and on-demand manufacturing

The ability to produce complex objects autonomously in a remote environment is highly sought after by resource extraction companies, space agencies, and the military alike. First working applications exist and many more are being developed and field tested.

3D printing can be used to bring manufacturing to remote, hard-to-access areas. In 2014 the US Navy installed 3D printers on the USS Essex to train sailors to print needed spare parts and weapon components, reducing lead time and enabling access to critical parts in remote situations. Another experimental project by the US Navy is the concept of 3D printing drones 'on demand' on board ocean-going vessels. The idea is that a ship would leave port already carrying a small number of electrical components and parts common to most drone designs. Then, depending on any given need – e.g., surveillance or intelligence – the sailors would be able to print and assemble the required drones by themselves.

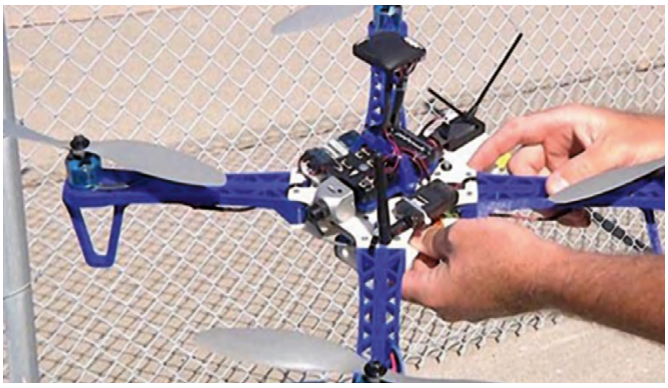

**Figure 21:** US Navy's 3D-printed drone; **Source:** 3ders

In aerospace, **NASA** has contracted the 3D printing company **Made in Space** to design a 3D printer to be tested at the International Space Station. Made in Space focuses on producing printers and materials for operation in space. The company's ultimate vision is to deliver the technologies necessary for manufacturing in space during deep space exploration missions. Paired with the idea of self-replicating 3D printers that **RepRap** has pioneered, this can also support the most complex space missions from the exploration of planets and comets to the exploitation of resource deposits on asteroids.[28]

[25] http://www.gereports.com/post/116402870270/the-faa-cleared-the-first-3d-printed-part-to-fly/
[26] http://www.airbusgroup.com/int/en/story-overview/factory-of-the-future.html
[27] http://www.airbus.com/newsevents/news-events-single/detail/airbus-tests-high-tech-concepts-with-an-innovative-3d-printed-mini-aircraft/
[28] http://www.madeinspace.us/projects/3dp/


**Figure 22:** The next level of 3D printing: Made in Space; **Source:** Made in Space

Resource extraction projects usually operate in remote areas with little or no access to infrastructure, which makes delivery of spare parts challenging. Oil platforms are a perfect example of this. **Shell's Technology Center** is exploring remote offshore 3D printing of production tools, with the aim of enabling platform crews to make their own tools.[29]

**Figure 23:** Innovation lab in Nepal; **Source:** All3DP

Remote communities in developing regions often also lack access to manufacturing capabilities and are disconnected from global supply chains. **Field Ready** is collaborating with **World Vision** to establish an innovation lab in Nepal to produce 3D-printed supplies needed by aid agencies in relief camps (which, in turn, will reduce the requirement to deliver kit supplies to disaster areas). The company estimates that this technology could save 40-50% of the logistics costs of aid agencies.[30]

## 2.4 New services and business models

The most natural business model is to offer a 3D printing service to anyone who doesn't own a printer. In the wake of the maker movement, so-called **"fabshops"** (fabrication shops) are opening up around the world; these offer 3D printing infrastructure access to virtually everyone. Designers and amateurs can use these shops to design and print objects, and collaborate on 3D printing projects. There are already 40 fabshops in Germany alone, and the company **TechShop** has established the first chain of fabshops in the US.[31] Business models vary; both for-profit and non-profit approaches exist.

3D printing can be a time-consuming process, particularly the early stage of generating a 3D model or image. A promising business model is therefore one that grants transparency to 3D printing services and offers online access to existing 3D models.[32]


**Figure 24:** A 3D printer at TechShop in San Francisco; **Source:** VentureBeat

[29] http://www.shell.com/inside-energy/3d-printing.html
[30] https://www.theguardian.com/globaldevelopment/2015/dec/30/disasteremergency3dprintinghumanitarianreliefnepalearthquake
[31] http://www.techshop.ws/3_D_Printing.html
[32] http://www.thingiverse.com/about/

**All3DP** provides a transparency platform that enables its customers to access, compare, and select the most suitable 3D printing services. **Thingiverse** is an online platform that allows users to share and swap their 3D printing designs. Acting as an online catalog for 3D printing files, this platform supports a community of 3D printing enthusiasts and allows feedback and suggestions to improve 3D models. Other similar platforms such as **Shapeways** and **Sculpteo** go beyond the Thingiverse portfolio to also offer object printing and delivery.[33]

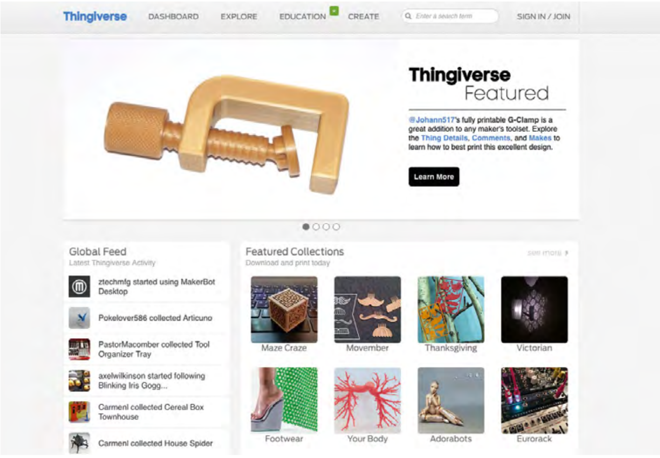


**Figure 25:** Design-sharing platform Thingiverse; **Source:** Thingiverse

Another line of services addresses the critical issue of data security in 3D printing. **3DTrust** offers secured and direct streaming solutions of encrypted printing data to remote 3D printers. This enables outsourcing and managing production from a company's headquarters to remote manufacturing sites, while maintaining control over intellectual property and products. Using 3DTrust's software, the design owners can track by whom and how many times a part has been printed in order to detect unauthorized usage of the file. In addition to security, this functionality also allows IP holders to monetize on every single 3D-printed reproduction of a virtual 3D model.[34]

## 2.5 Upcoming 3D printing technologies

As 3D printing technology advances, companies and consumers can take on increasingly ambitious projects that are larger in scale and more complex, and they can utilize a greater variety of materials.

One example of using 3D printing to produce large, complex structures is the Dutch 3D start-up that is using 3D printing robots to build a bridge made of printed steel; on completion in 2017 this bridge will span one of Amsterdam's famous canals. Besides bridges, 3D printing is also being tested as a way to potentially build houses in the future.

In Beijing, China, **HuaShang Tengda** managed to 3D print and construct a 400-square meter home in just 45 days.[35] This provides an exciting glimpse of how 3D printing could alleviate predicted housing shortages; it also suggests 3D printing could help to quickly create dynamic environments for retail and warehousing purposes.

**Figure 26:** 3D printing large, complex structures; **Source:** Static

[33] http://www.shapeways.com
[34] http://3dtrust.de/
[35] https://3dprint.com/138664/huashang-tengda-3d-print-house/

In terms of materials that can be used for 3D printing, one new frontier is food. 3D printers are producing colorful layers of sweets around the world. Another example is Food Ink, a pop-up 3D printer restaurant launched in London in mid-2016, which opened with the promise of delivering not just a meal but gourmet cuisine from "pixels to printer to plate". Food Ink produces its dishes with the multi-material 3D printer by Flow, in which food pastes get heated and combined in several layers. There's a variety of dishes and each one is planned to the smallest nutrient. Best of all, this type of cooking produces hardly any waste.[36]

**Figure 27:** The first 3D-printing restaurant; **Source:** Food Ink

A future example illustrating the mind-boggling possibilities for 3D printing to create complex structures efficiently is the concept of molecular printing. Chemists at the **University of Illinois** have succeeded in creating a machine that combines molecules similar to the process of layering used by 3D printers. This enables billions of new chemical links, and the creation of synthetic chemicals, all at a much lower cost than current processes for creating complex molecules.[37]

**Figure 28:** Molecular printing using 3D printing; **Source:** The Scientist

The evolution of 3D printing is poised to bring radically new applications. **MIT** is currently testing 4D printing which adds the dimension of change to 3D-printed objects. 4D-printed items can self-assemble and adjust shape when confronted with a change in their environment (e.g., when they are immersed in water or experience a change in temperature). Possible future applications span multiple industries. Imagine water pipes that shrink or expand depending on water flow, or tires that adapt to wet surfaces and change back to their original size and pressure when the roads are dry again.

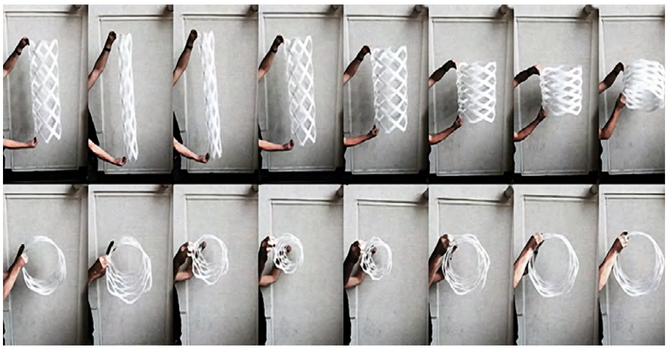

**Figure 29:** Designed for change: The new era of 4D printing; **Source:** 3D Print

[36] http://foodink.io/
[37] http://news.asiaone.com/news/asia/architectssay3dprintedhousechinacanwithstandearthquakes

# 3 IMPLICATIONS OF 3D PRINTING FOR FUTURE SUPPLY CHAINS

Going back to the big picture questions raised in chapter one, will 3D printing really disrupt global manufacturing? Will 3D printing render traditional manufacturing factories obsolete? And consequently, will logistics volumes be disrupted?

It is relatively clear that 3D printing will not be used to mass produce anything and everything such as run-of-the-mill commodity goods. Instead, the promising advantages and applications of 3D printing highlighted in the previous chapters illustrate that the technology's greatest potential lies in its capability to simplify the production of highly complex and customizable products and parts.

For companies involved in this type of manufacturing, 3D printing could become a disruptive force that in future redefines traditional manufacturing and supply chain strategies.

To generate first ideas on future scenarios, below are five use cases illustrating how companies can work together with logistics providers to integrate 3D printing into their supply chains. And this chapter concludes with a step-by-step approach as to how companies can proceed with assessing the implications and potential of 3D printing in their unique supply chains.

## 3.1 Spare parts on demand

A quick search online will reveal that almost all leading 3D printing publications and studies mention the spare parts sector as one of the first areas to be disrupted by the proliferation of 3D printing.[38] Why is this?

At present, hundreds of millions of spare parts are kept in storage all across the world to service products as diverse as cars to watches to x-ray machines. Although most spare parts warehouses have a high proportion of fast-moving items, many items will rarely be used and some may never actually be needed. Case studies estimate that the actual share of excess inventories can sometimes exceed 20%.[39] Not only is it costly for companies to store this unused stock but it also builds inefficiency into the supply chain, as excess inventory is being produced with no guarantee that all parts will ever come into use.


**Figure 30:** Spare parts on demand

[38] https://3dprintingindustry.com/news/kazzata-first-marketplace-3d-printed-spare-parts-27567/
[39] http://www.industrialsupplymagazine.com/pages/Management---Value-of-excess-inventory.php

Thanks to 3D printing, companies may no longer need to store spare parts physically in a warehouse. Instead, they can print these parts on demand, where required, and rapidly deliver these items to the customer. In order to achieve coverage and efficiency in lead-time reduction, logistics providers could support companies in creating a dense network of 3D printers to instantly print and deliver spare parts on demand.

The virtual print files of spare parts would be securely stored in software databases that essentially act as a "virtual warehouse". One organization that has already developed and implemented this type of virtual warehouse concept is **Kazzata**. The company aims to provide an online marketplace for spare parts, effectively establishing a CAD repository for obsolete and rare parts.[40] When a part is required, users can simply search for the right part and send the file to the nearest 3D printer.

Many companies are already embracing the concept of printing spare parts; a good example of this is the most recent news from **Mercedes-Benz Trucks**. In an effort to resolve backlogs in spare parts delivery, the trucking company announced it will now allow customers to 3D print more than 30 different spare parts for cargo trucks. Customers no longer have to face a lengthy wait for original factory spare parts to be delivered. Instead they can have the part printed at the nearest facility and delivered in less time.

Companies can also make use of their logistics providers' future end-to-end spare parts on-demand solutions. Each logistics provider can achieve economies of scale by building up an owned network of shared 3D printers located in warehouses and distribution centers around the world. In the same way as many companies today provision spare parts to a third-party logistics provider, in future companies will be able to entrust their logistics provider to efficiently process, print, and deliver spare parts orders in a fast, low-cost manner.

**Figure 31:** Spare parts from a 3D printer; **Sources:** The Loadstar, DHL

**DHL** has tested this future concept by 3D printing replicas of spare parts that the organization currently stores for automotive and technology customers. These tests concluded that the costs for materials, hardware, and handling of the 3D printed spare parts did not yet result in a viable business case. Furthermore, it proved challenging to print and deliver the spare parts fast enough to meet service level agreements – with some complex and larger parts taking several days to print.

However, it was interesting to discover that the quality of the printed parts almost equaled that of the existing spare parts. This strongly suggests that, as 3D printing costs decrease, on-demand production of spare parts will be inevitable.

[40] https://blog.kazzata.com/about/

## 3.2 Individualized direct parts manufacturing

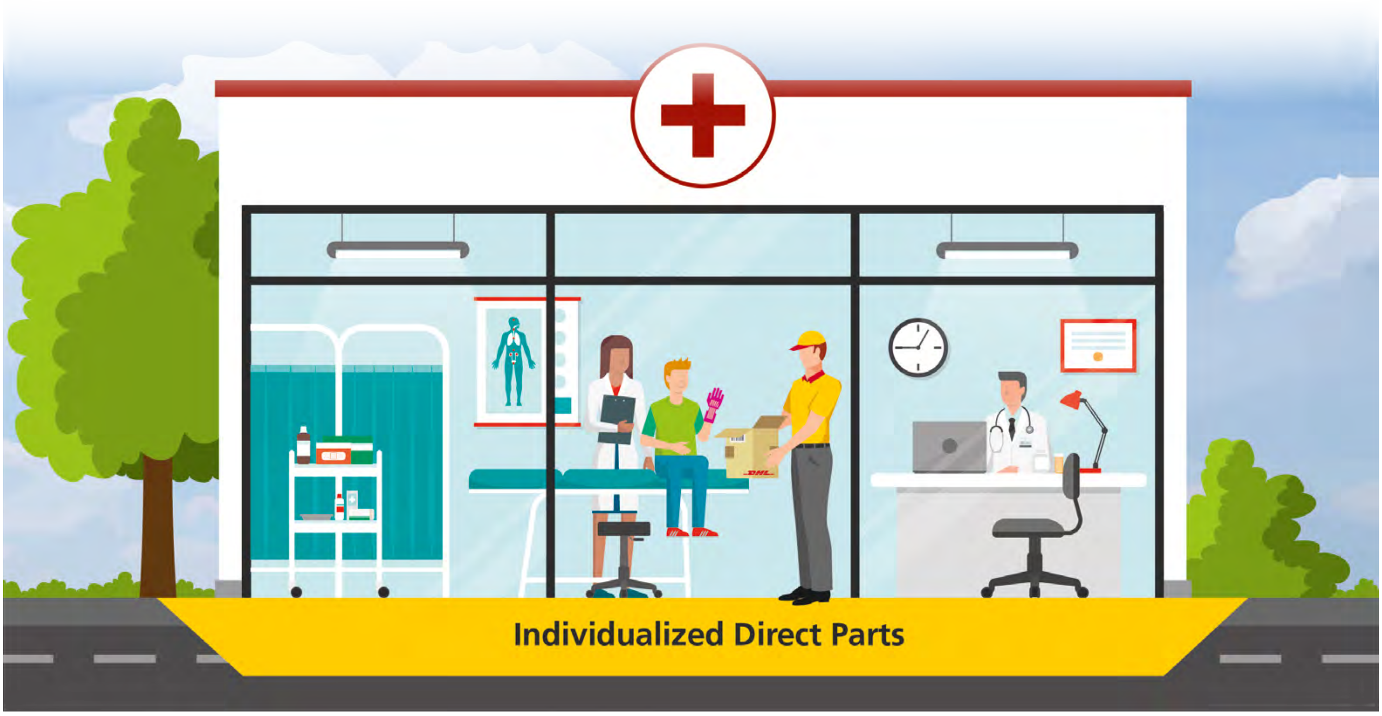


**Figure 32:** 3D printing enables high levels of customization

As highlighted in chapter two, there are many exciting examples of companies in aviation, automotive, healthcare, and other industries using 3D printing to produce individualized parts.

When customers require high levels of customization, 3D printing can represent a source of competitive advantage for the organization; companies are incentivized to create tailored parts that can be delivered quickly to the point of use.

**Figure 33:** From dental crowns to prosthetics – 3D printing allows a new level of customization; **Source:** Lumecluster

As with the previous example of spare parts on demand, companies can work with logistics providers to create a network of 3D printers, each of which acts in essence as a small micro factory. These printers can be located in regional warehouses or local distribution centers and can be branded with an OEM's label.

Healthcare is a key industry capable of leveraging such a concept. Already the healthcare industry is using 3D printing in many different areas and achieving quality standards on a par with traditional manufacturing methods. From small practices to large hospitals, all kinds of healthcare facilities can collaborate with medical companies and logistics providers to create an end-to-end 3D printing service that reduces cost and complexity through operating to scale.

For example, instead of dealing with multiple suppliers and deliveries per day, 3D printing warehouses operated by logistics providers can take care of the sourcing of materials as well as the manufacture of individualized parts (e.g., personalized prosthetics, custom-fitted knee replacements). The logistics provider can also ensure fast, safe, and secure delivery of each part to the right location precisely when required.

Another future vision is the idea of manufacturing individualized parts not in a stationary location such as a warehouse but in a moving vehicle. This can additionally reduce delivery lead times. **Amazon**, for example, has filed a patent for a truck fitted with 3D printers, with the intention of manufacturing products on the way to a customer destination.[41] At scale, this could enable companies to produce parts very close to demand and thereby drastically reduce the lead time of individualized parts delivery to customers.

**Figure 34:** Personalized, one-of-a-kind production; **Source:** Indiatoday

## 3.3 Product postponement services

Utilizing 3D printing in postponement strategies could be another option to enable higher levels of product customization, something that's becoming more and more important for both business customers and consumers alike.

A recent study by Bain & Company on online shopping preferences found that, while only 10% of online shoppers have used product customization options so far, up to a third are interested in doing so in future. The study further revealed that online shoppers who had used customization options before scored significantly higher than other shoppers on the customer loyalty test.[42]

To increase customization options but at the same time reduce lead times to the customer, companies can partner with logistics providers that offer postponement services using 3D printing. By delaying final assembly to the final point of demand, companies can give their customers access to a wide variety of customization options – they can select aspects of the design, material, shape and size, packaging, and product functionalities.

Local distribution centers can hold stock of almost–finished goods as well as 3D printers that execute a variety of customization functions before the product is delivered to the customer. Where current customization might include an engraved name on a smartphone or a personalized message inside the packaging, 3D printing would allow companies to deliver the smartphone, for example, in a truly personalized, one-of-a-kind protective case in an incredibly short window of time.


**Figure 35:** Product postponement services

[41] https://3dprintingindustry.com/news/amazon-sets-out-to-conquer-entire-3d-printing-industry-with-new-patent-application-43263/
[42] http://www.bain.com/Images/BAIN_BRIEF_Making_it_personal.pdf

Such concepts are being tested by **Adidas** which is opening speed factories that use 3D printing and automation technologies. Here the company is creating custom shoes that are assembled and delivered closer to demand.

**Figure 36:** Made-to-measure footwear; **Source:** Adidas

## 3.4 End-of-runway services

End-of-runway services typically encompass integrated logistics solutions located at specific warehouses in direct proximity to important airport hubs. This is how logistics providers can achieve fast response times and speed to market for time-sensitive shipment of critical parts, even after latest order cut-off times. In addition to conventional warehousing services, a major focus for end-of-runway services are sector-specific service offerings and integrated return and repair services. This is where the strengths of 3D printing can be leveraged.

**Figure 37:** Printed, packed, and ready to fly; **Source:** DHL

As the speed of 3D printing increases, it is highly applicable in end-of-runway hubs to enable fast production of parts that need to be put into operation in the shortest possible timeframe. Relevant fields of application include spare parts for commercial energy (e.g., renewable energy plant spare parts or the production of brake pads for wind turbines) and for the engineering and manufacturing sector (e.g., fuel nozzles for aircraft).

Besides industrial applications, 3D printing can also be used in end-of-runway logistics to improve repair operations in the consumer sector that have to be covered under warranty. Necessary replacement parts can even be printed and delivered immediately, reducing lead times and improving levels of customer satisfaction.

Such an integrated concept is being used by **UPS** with its investment in **Fast Radius**. Fast Radius has strategically located its 3D printing factory just minutes from the UPS global air hub. The value of this end-of-runway location is that orders can be manufactured up to the 1 a.m. pick-up time and be delivered anywhere in the U.S. the next morning.[43]

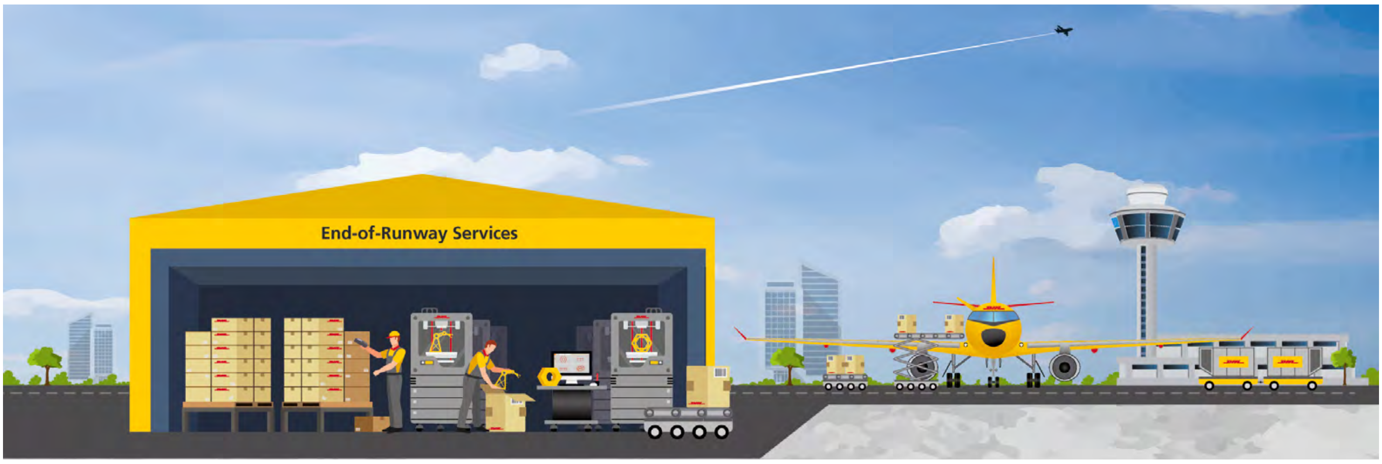


**Figure 38:** End-of-runway services for a faster response

[43] http://www.logisticsmgmt.com/article/ups_rolls_out_plan_for_full_scale_on_demand_3d_printing_manufacturing_netwo

## 3.5 3D print shops for businesses and consumers

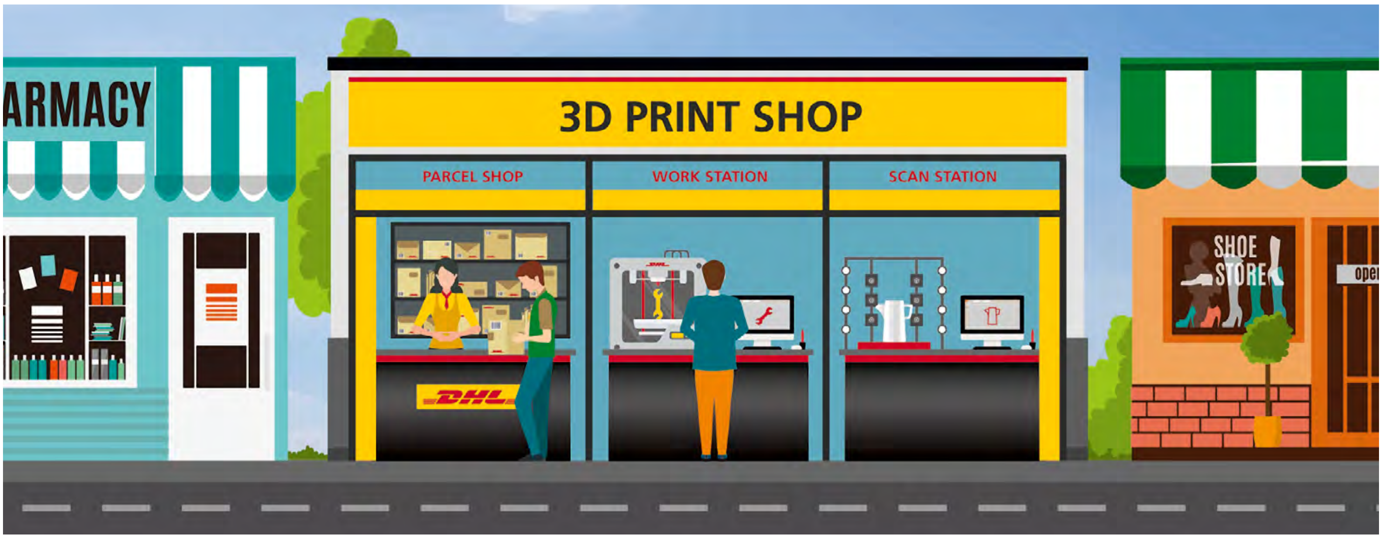


**Figure 39:** Easy access to 3D printing capabilities

In contrast to the above use cases that focus primarily on leveraging logistics to provide new 3D printing services, businesses and consumers can also use future networks of 3D print shops for a variety of applications.

In the consumer context, one application could be for companies to retrofit their many service points or retail points with a 3D printing infrastructure. In essence, this would allow them to offer local communities access to state-of-the-art 3D printing services. The root of this concept is not new; it would work in a similar way to how consumers currently print paper documents by taking a file on a USB drive to their local copy shop or print photos at a photo kiosk in stores (see figure 40). Looking into the future, these 3D print shops could eventually integrate not just 3D printers but also design tools and scanners, as well as a wide selection of materials.

3D print shops like this could also be used by companies to rapidly prototype new products without having to invest in and maintain the latest 3D-printing infrastructure. These facilities could also serve local businesses such as architects and small design studios that need to produce 3D models, as well as craftspeople creating tailor-made items for their customers. Personnel working inside 3D print shops will be trained to offer varying levels of support to match each customer's 3D printing skillset. And because the printing process itself can take some time, the 3D print shop could also offer a delivery service to its customers.

First steps have already been taken in this direction. DHL, which operates tens of thousands of service points worldwide, tested a pop-up 3D print shop concept in 2013. DHL offered to 3D print individualized consumer goods and to scan and reproduce consumer products that were handed in by DHL employees. This reproduction service proved to be technically challenging. Not all items were suitable for reproduction and most required CAD post-processing (although, as 3D imaging technology improves, this particular challenge can be overcome).

Out of the many items handed in, only about 10% could be reproduced functionally and ultimately the costs far exceeded the willingness to pay. Despite these challenges, the DHL pilot revealed high levels of interest in 3D printing objects in future. To enable a 3D print shop, key success factors will be the ability to provide a range of printing materials and low operating costs.


**Figure 40:** Using 3D print shops could one day be as normal as printing pictures or documents in stores today; **Source:** Kodak

## 3.6 How to assess 3D printing for your supply chain

The use cases in this chapter indicate various ways that companies can leverage 3D printing in the supply chain to increase operational excellence as well as to improve the customer experience. However, to understand the full implications of 3D printing in a company's supply chain, it is necessary to consider each company's operating environment, manufacturing capability, customer needs, and product portfolio.

For companies that believe 3D printing could have high relevance for their manufacturing and supply chain strategy, below are some next steps on how to assess the potential for 3D printing in future supply chains.

### 3D printing assessment journey:

**1. Analyze your products and organizational capabilities:** The first step is to look into your organization to assess current 3D printing capabilities and identify where there are any gaps and whether there's a need to bring in external expertise. After this exercise, companies can begin to analyze their current and future product portfolios in order to identify products that can be 3D printed and/or could benefit from 3D printing technology. For example, could 3D printing enable new product geometries that are more efficient? Or could 3D printing enable new personalization options that would deliver additional value to the customer?

Once this list has been developed, the next step is to prioritize products based on suitability for 3D printing and the benefits that can be achieved from 3D printing. Companies should prioritize highly complex and customizable products over generic items that have no inherent need for customization. An additional aspect could be to prioritize products that are currently produced in small batch sizes, such as spare parts.

**2. Create your transformation roadmap:** From the gap analysis of 3D printing capabilities in the organization and from the prioritized list of products (step 1), companies can then develop a step-by-step roadmap to successfully transform and integrate 3D printing into the organization. This can be achieved by assessing the near-term and long-term feasibility of 3D printing in the manufacturing supply chain (in terms of a business model based on material and printer costs, time for production, quality, etc.). It is valuable to engage with a logistics provider in this step to factor in the logistics implications as well as potential new ideas for savings and innovative business models.

**3. Adapt and implement 3D printing into your manufacturing supply chain:** The final step is to adapt current manufacturing and supply chain strategies and ensure successful integration of 3D printing into the organization. Companies need to focus on working together with partners to redesign and optimize the manufacturing supply chain (e.g., to establish a network to leverage spare parts on demand or to utilize end-of-runway services). As 3D printing is a fast-developing technology, today's technology investments will probably be outdated in just a few years' time. So it makes sense to start with several pilots with the most promising product segments and then move towards a full-scale transformation and implementation as the success factors in chapter one are achieved. At this stage, companies should also continuously build up their organization's resources and capabilities to embrace 3D printing.

# CONCLUSION AND OUTLOOK

Encouraged by opportunities for greater customization, less waste, and more localized manufacturing and delivery, companies across many industries are showing more and more interest in 3D printing for manufacturing and as a source of new business models.

Our assessment shows that 3D printing is likely to complement rather than entirely substitute traditional manufacturing techniques. Simply put, not all products can and should be 3D printed. This conclusion is echoed in a recent survey which revealed that 38% of companies anticipate using 3D printing in their serial production within five years but not necessarily to completely replace traditional manufacturing.[44]

However, that is not to say that 3D printing will not be disruptive. 3D printing is likely to substitute traditional manufacturing in industry segments that produce highly complex and customized goods. This is, in fact, already happening in aviation, automotive, and medical and healthcare applications. To achieve wider application and adoption, companies must collaborate and innovate in order to overcome 3D printing's remaining challenges – such as speed of production, cost, and limited material inputs.

In logistics, 3D printing will play a much more prominent role in the areas of spare parts logistics and individualized parts manufacturing. As manufacturers adapt their production processes and supply chains, this will open new opportunities and will also challenge logistics providers to find new customer-centric solutions. Some product ranges may be produced entirely on demand through 3D printing, and new regional and last-mile logistics solutions will be required.

Looking ahead, 3D printing will undoubtedly be a game changer in many industry segments, improving product quality and, in some cases, enabling companies to generate completely new products that were previously not possible.

At DHL, we look forward to working with customers and partners to jointly explore new solutions to unlock the potential of 3D printing in future supply chains.

[44] Ernst & Young's Global 3D Printing Report, 2016

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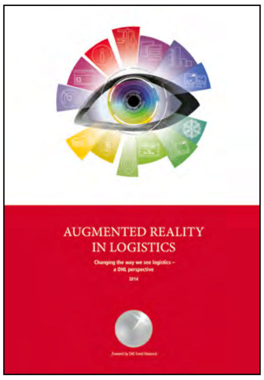


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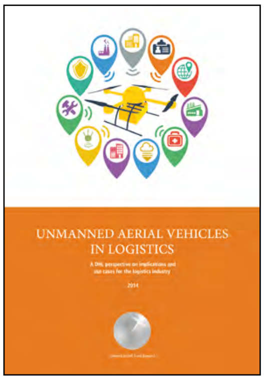


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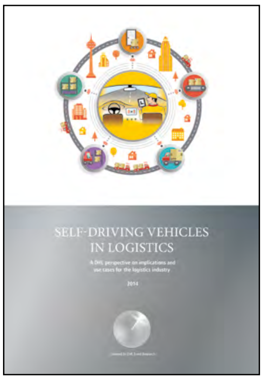
SELF-DRIVING VEHICLES IN LOGISTICS

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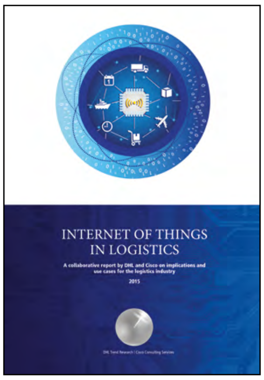
INTERNET OF THINGS IN LOGISTICS

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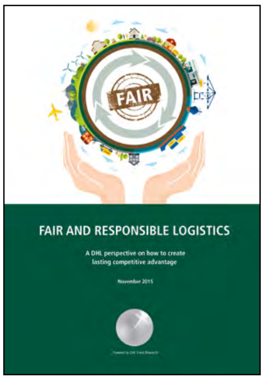
FAIR AND RESPONSIBLE LOGISTICS

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ROBOTICS IN LOGISTICS


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