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A Study on 3D Printing and its Effects on the Future of Transportation

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16. Abstract

In recent years, significant progress has been made in additive manufacturing (AM) for numerous applications in various industrial segments. International Data Corporation (IDC) forecasts the global market for 3D printing technology to exceed $14 billion in 2019. It is expected to double in the next five years. 3D printing technology can fabricate complex geometries with no part-specific tooling and much less waste material, and can produce various customized products at lower cost. An MIT study indicates that the adoption of 3D printing can reduce supply chain costs by 50% to 90%, this being particularly true for slow-moving and custom products (Bhasin and Bodla 2014). Bulk of the savings for traditional manufacturers would come from the reduction of transportation activity and worldwide goods transfers. A possible decline in the air cargo and the ocean container businesses because of 3D printing is 41% and 37% respectively. Also, 25% of the trucking freight business is exposed to decline. 3D printing technology brings the production closer to the consumer, so production and distribution of products could begin to be deglobalized. Therefore, 3D printing technology is likely a disruptive innovation that will affect the logistics industry and the global supply chain. Moreover, products can be fabricated on demand without the need to build up inventories or warehouse new products and spare parts. This report presents an overview of the potential impact of 3D printing technology and its future on the transportation sectors related to logistics, supply chains, and freight. It is noteworthy that over 30% of imported goods in the US are potentially suitable for manufacture by 3D printing technology, so there is a high probability that 3D printing will create new high-tech jobs, and produce a shift in the current labor market. However, there is significant economic benefit when AM technologies are integrated with traditional manufacturing shops. This report does not speculate on that shift, but summarizes existing research to better understand how 3D printing could affect the current market of $2.4 trillion in goods imported into the US.

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1 ABSTRACT

In recent years, significant progress has been made in additive manufacturing (AM) for numerous applications in various industrial segments. International Data Corporation (IDC) forecasts the global market for 3D printing technology to exceed $14 billion in 2019. It is expected to double in the next five years. 3D printing technology can fabricate complex geometries with no part-specific tooling and much less waste material, and can produce various customized products at lower cost. An MIT study indicates that the adoption of 3D printing can reduce supply chain costs by 50% to 90%, this being particularly true for slow-moving and custom products (Bhasin and Bodla 2014). Bulk of the savings for traditional manufacturers would come from the reduction of transportation activity and worldwide goods transfers. A possible decline in the air cargo and the ocean container businesses because of 3D printing is 41% and 37% respectively. Also, 25% of the trucking freight business is exposed to decline. 3D printing technology brings the production closer to the consumer, so production and distribution of products could begin to be deglobalized. Therefore, 3D printing technology is likely a disruptive innovation that will affect the logistics industry and the global supply chain. Moreover, products can be fabricated on demand without the need to build up inventories or warehouse new products and spare parts. This report presents an overview of the potential impact of 3D printing technology and its future on the transportation sectors related to logistics, supply chains, and freight. It is noteworthy that over 30% of imported goods in the US are potentially suitable for manufacture by 3D printing technology, so there is a high probability that 3D printing will create new high-tech jobs, and produce a shift in the current labor market. However, there is significant economic benefit when AM technologies are integrated with traditional manufacturing shops. This report does not speculate on that shift, but summarizes existing research to better understand how 3D printing could affect the current market of $2.4 trillion in goods imported into the US.

2 INTRODUCTION

Additive manufacturing (AM) is a revolutionary emerging technology that could up-end the last two centuries of design approaches in traditional manufacturing. It also has the potential to produce disruptive changes to the economy, the environment, and global logistics (Campbell et al. 2011). Since 1984, the concept of AM has advanced, making it possible to fabricate a 3D object layer by layer. The application of 3D printing with photopolymer resin was patented in 1986 (Gibson, Rosen, and Stucker 2015). Since then, AM technique has improved and developed significantly. See timeline, Figure 1. AM technology involves many methods, including powder bed fusion (PBF), stereolithography (SLA), materials extrusion or fused deposition modeling (FDM), and inkjet printing (Ngo et al. 2018).

3D AM techniques have several advantages. One can fabricate sophisticated products, maximize materials saving, and customize products while benefitting from low costs. 3D printing products can range from creative novelty items to the prospect of manufacturing tools in space or even constructing customized buildings using moon dust. According to the Economist in 2012, 20% of the output of 3D printers is now final products, rather than prototypes, and the percentage will rise to 50% by 2020 (B. Berman 2012). Estimated global spending on 3D printing technology was $11 billion, and is projected to reach about $23 billion by 2022 (Framingham 2018). Unlike conventional manufacturing processes, in which many parts must be assembled, 3D printing can produce large pieces of a final product in one process. Moreover, 3D printing can simplify the extended supply chain by which conventional parts are often shipped from many factories around the world (Campbell et al. 2011). 3D printing could transform manufacturing and affect logistics systems in a few years. In AM process, a product's design as a digital file would move very quickly around the world to be printed anywhere by any 3D printer. So, the final products can be printed at any location including the customer's site instead of being shipped from remote parts stores. 3D has the disruptive capability to replace essential segments of mass production and much of the supply chain that supports it (Ankner and James 2017).

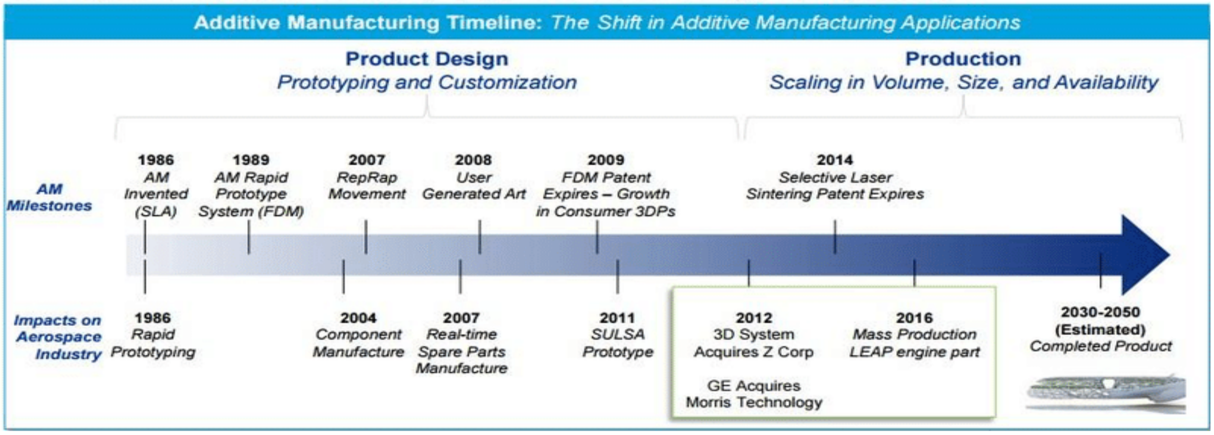


Figure 1 Shows the timeline of Additive Manufacturing process (Columbus 2015).

3D printing has been applied widely in different industries including automotive, aerospace, biomedical, and construction. The tremendous growth of 3D printing will continue to emerge in development to make it more efficient and cost effective. The industry is interested in reducing the cost of products, producing complex structure from different materials, and increasing 3D printer capabilities to become faster, and more accurate. These efficiencies run the gamut from the cost of distribution to assembly lines, inventory, and ultimately the product itself.

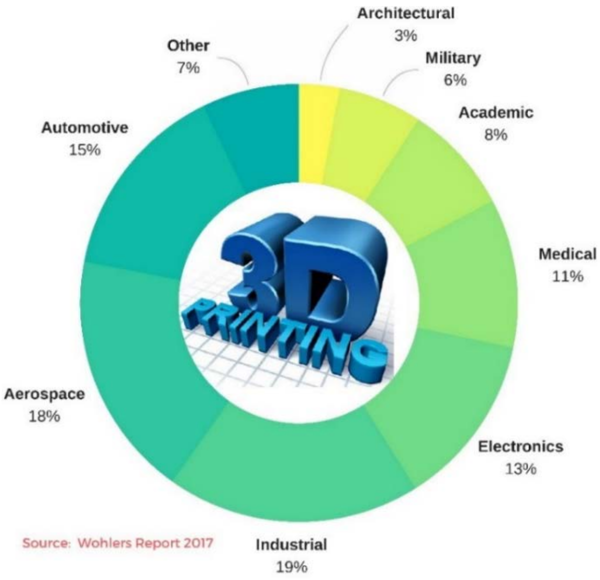


Figure 2 Shows industries that use 3D printing (Wohlers Report 2017).

Recent reports and studies suggest that AM development is gaining momentum and possibly reaching a take-off point within the next decade. The trend toward more investment in 3D printing technology will change future supply chains significantly, as production will move from make-to-stock in offshore/low-cost locations to make-on-demand closer to the final customer. Thus, the global supply chain for many products may be simplified or eliminated. The transportation, volume of freight business, and inventory costs would be influenced as well. This motivates us to provide a brief overview of the potential impact of 3D printing technology on the transportation industry.

3 3D PRINTING TECHNOLOGY

Recently, 3D printing has attracted significant attention and captured the imagination of everyone from entrepreneurs to at-home hobbyists. 3D printing is an additive manufacturing process that adds many layers of the materials upon layers until the product is built. 3D printing uses a computer-aided design (CAD) or laser scan to create a 3D object (Birtchnell and Hoyle 2014). The design model is sliced into several plans, which direct the 3D printer in depositing the successive thin layers of material upon each other to construct a final product. Figure 3 illustrates the essential steps of the 3D printing process.

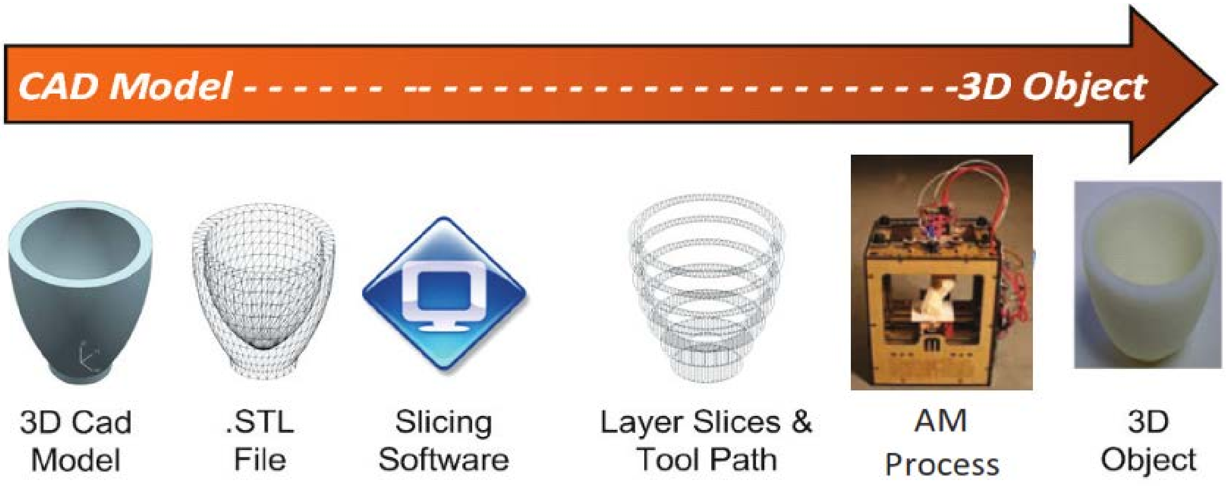


Figure 3 General steps of the 3D printing process (Campbell et al. 2011).

The 3D printing technique produces an assembled unit and reduces the number of separate components, thereby involving fewer suppliers of raw material. AM process offers the ultimate geometric freedom in engineering design to create complex shapes that cannot be produced by any other means. For example, curved internal cooling channels can be integrated into components (Khajavi, Partanen, and Holmström 2014).

AM process creates the object from bottom-up by adding layers. So, it is more efficient of the environment because there is very little waste material compared to traditional manufacturing (Ankner and James 2017). Conventional manufacturing processes such as casting and forming create the object from bulk raw materials, while subtractive machining such as milling, and turning create the objects from the top-down by subtracting and removing materials until getting the final product. Figure 4 presents a list of common subtractive and additive manufacturing methods.

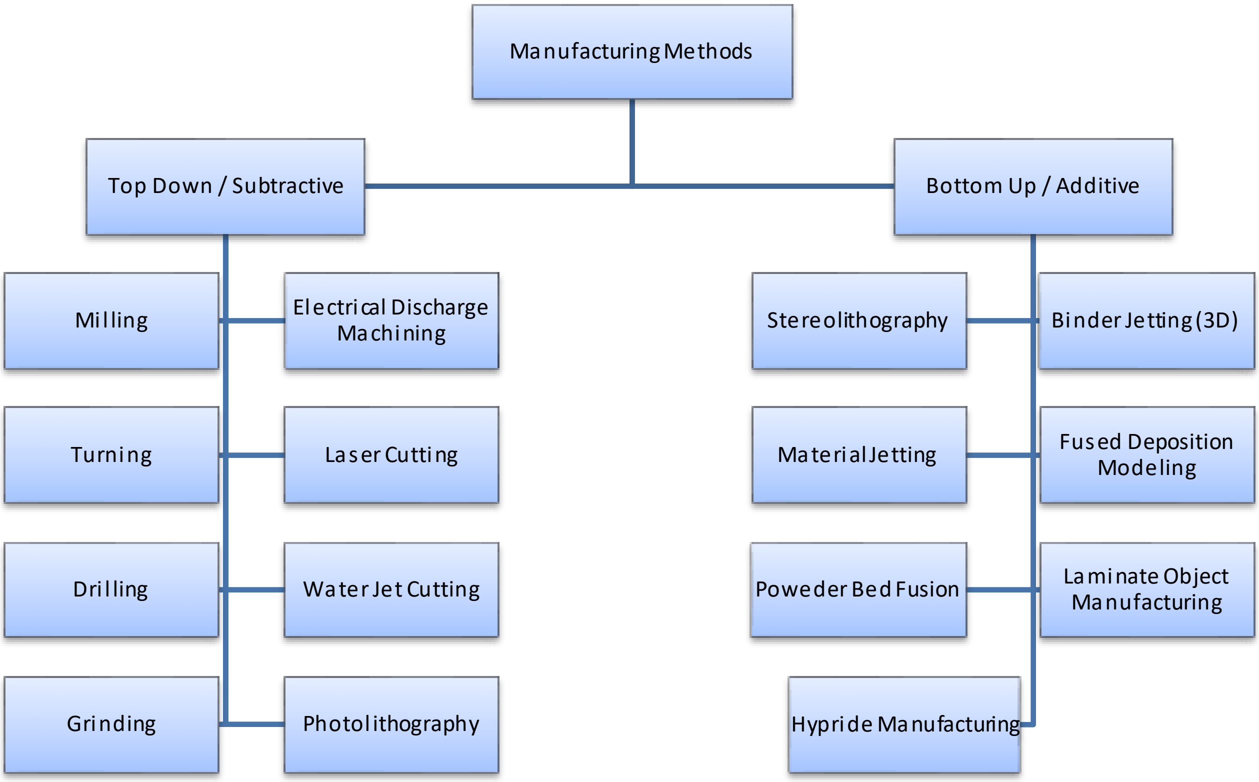


Figure 4 Schematic shows manufacturing process including subtractive and additive processes.

In traditional manufacturing processes, the final product is limited by the capabilities of the tools that are used in the process. But in 3-D printing, those constraints no longer matter, as the engineers start designing for function rather than designing for manufacturability (Hessman 2015). Therefore, the engineers and designers are liberated to make the best part possible to perform its function in the best way possible. Consequently, new opportunities exist for design in various industries (Campbell et al. 2011). AM is a single tool process that allows the direct production of parts without molding, making it uniquely capable of producing customized products with better profit potential. 3D printing technology enables small quantities of customized goods to be produced on demand, eliminating the need for large inventory and reducing transportation costs considerably (Birtchnell and Hoyle 2014).

Out of date equipment, or unique parts that would require costly new molding or manufacturing processes, can be scanned and re-fabricated in the 3D printing process lower cost. 3D printers are utilized in many sectors such as automotive replacement parts, the aerospace industry, medicine, prosthetics / artificial limbs, the aviation industry, the clothing industry, and even in foodstuff. Figure 5 shows AM standard structure (Scott 2016).

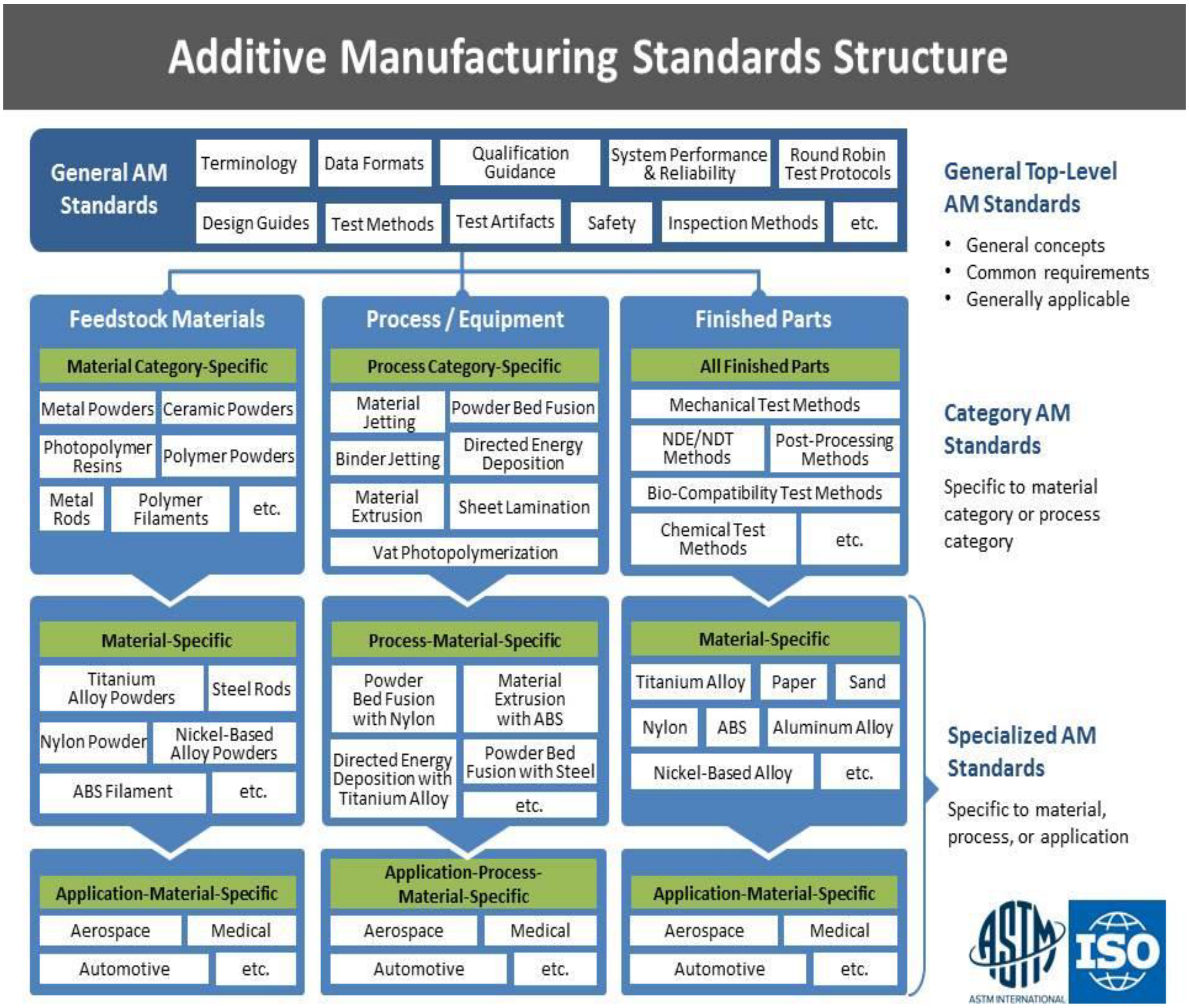


Figure 5 Standards structure approved by ASTM F42 and ISO TC261 (Scott 2016).

3.1 METHODS OF AM

Most common methods of AM have been developed to meet the demand for production of a large complex structure with fine resolutions using a wide range of materials. AM technology includes many methods such as stereolithography apparatus (SLA), powder bed fusion (PBF), fused deposition modeling (FDM), binder jetting (3D Printing), directed energy deposition (DMD), laminated object manufacturing (LOM), and hybrid manufacturing technologies. These methods are introduced briefly in Appendix I along with their descriptions, applications, suitable materials, advantages, and drawbacks. More details and comprehensive review are found elsewhere (Bhushan and Caspers 2017, Sandeep and Chhabra 2017, and Gibson, Rosen, and Stucker 2015). Today, there are many different 3D printing processes. However, a 2016 survey of Sculpteo revealed that powder bed fusion (PBF), fused deposition modeling (FDM), material jetting (MJ), and stereolithography (SLA) are the 3D technology most used by the respondents (De Wargny 2016).

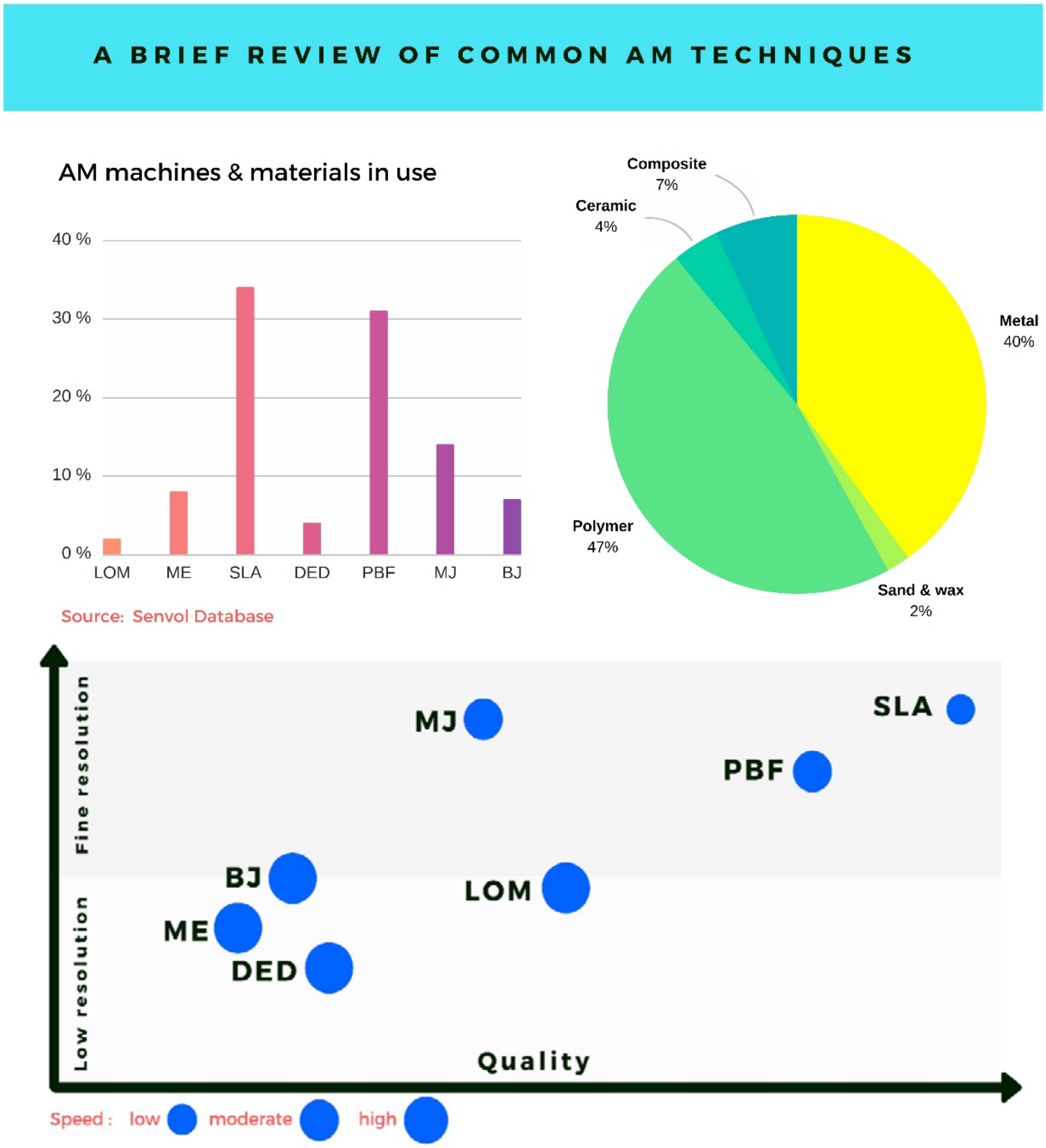


Figure 6 A brief review of common AM techniques.

3.2 AM METAL TECHNOLOGY

Metal printing is considered the holy grail of additive manufacturing and 3D printing. Powder bed fusion (PBF) that uses the laser as heat source, is the most widely applied AM metal technology that is used to print a range of metal alloys. It has found its path in the aerospace, aircraft, automotive, and healthcare industries for a variety of high-tech prototyping to low-volume final part production (Mouzakis 2018). Currently, metal 3D printing has limiting factors such as high cost of powder, distortion and residual stress. So post-processing may be required to develop the desired properties. Some vendors offer open architecture, allowing greater access to process parameters and machine interfaces, assisting in the development of certified and qualified process procedures. Systems range in price from a few thousand dollars to millions of dollars, depending on size, laser or electron beam power, and optional capabilities such as powder recycling or system diagnostics (“Price Compare 3D Printers” n.d.). Machine builders and service providers of metal AM systems along with their process names are shown in Table 1.

Table 1 Some vendors and service providers of PBF and DED AM metal systems.

Manufacturer			
EOS	eos.info/en	Direct Metal Laser Sintering	PBF laser
Concept Laser	concept-laser.de/	LaserCUSING®	PBF laser
3D Systems	3dsystems.com/	Selective Laser Melting	PBF laser, FDM
Arcam AB	arcam.com/	Electron Beam Melting	PBF electron beam
DMG Mori	us.dmgmori.com/	Direct Metal Deposition	DED laser
Sciaky	fabrisonic.com/	Ultrasonic additive manufacturing	UAM

3.3 AM TECHNOLOGY MARKET

Information about situations where additive manufacturing is being applied is not widely published. Hence, forecasts from multiple sources are used below to provide an estimate of the market size, taking the average of all prediction values per year as shown in Figure 7 (Dijk 2016).

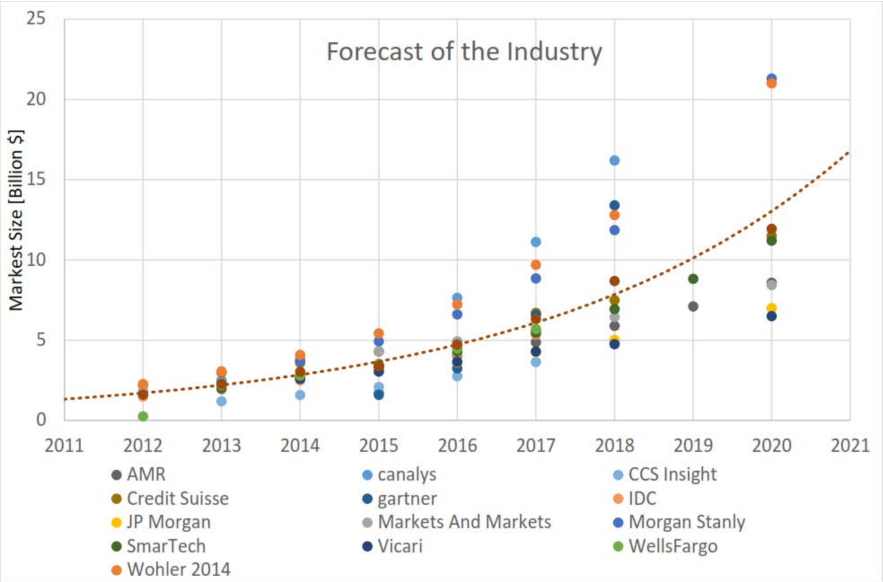


Figure 7 Forecast of the Industry (Dijk 2016).

Thus, the predictions suggest that the overall market size of AM technology has enormous growth potential in the next couple years. This is consistent with Gartner’s Hype Cycle in Figure 8, that shows five different stages of expectations for the 3D printing trend: being on the rise, being at its peak of expectations, sliding into the through, climbing the slope of enlightenment and finally entering the plateau of productivity (Richardot 2017). It shows that the emerging technologies have the accelerating maturity of enterprise 3D printing. The accelerating growth and diversity of 3D products suggests that a tipping point may be reached well within a decade, especially for major 3D susceptible industries. Therefore, some companies are already betting on the success of 3D printing for their businesses by making significant investments. In 2016, many companies such as Mercedes-Benz Truck, HP, GE, BMW, and Nikon have launched multimillion-dollar investments into the 3D printing technology (Chung et al. 2016).

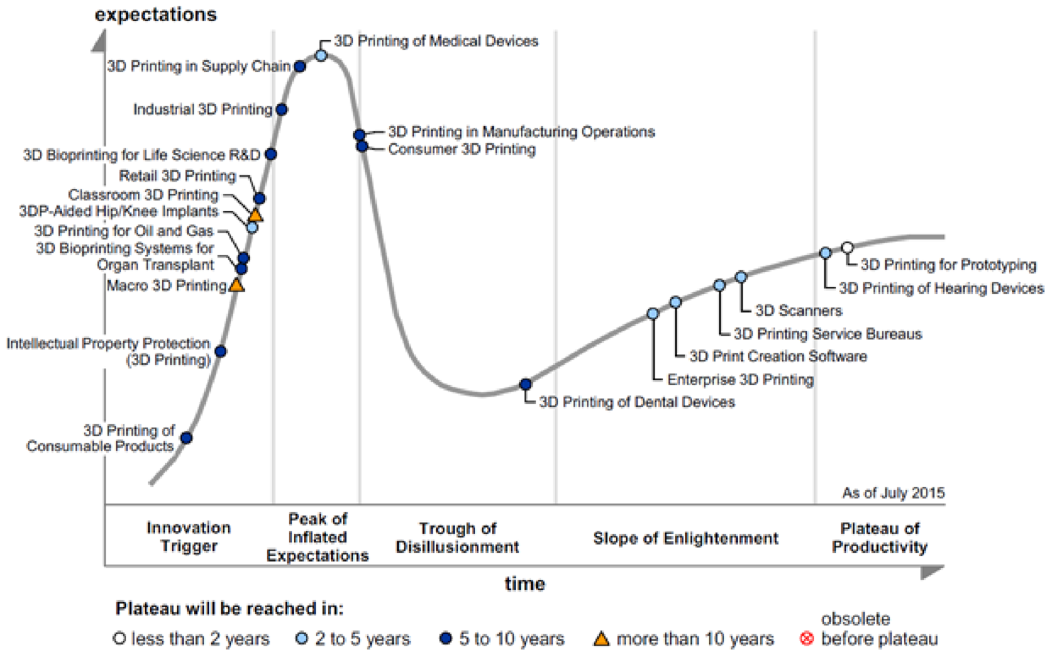


Figure 8 3D printing in the Gartner Hype Cycle. (Richardot 2017).

Figure 9 emphases of projected global 3D growth within major industrial markets (“3D Printing Market Size, Share and Trends Analysis Report” 2018).

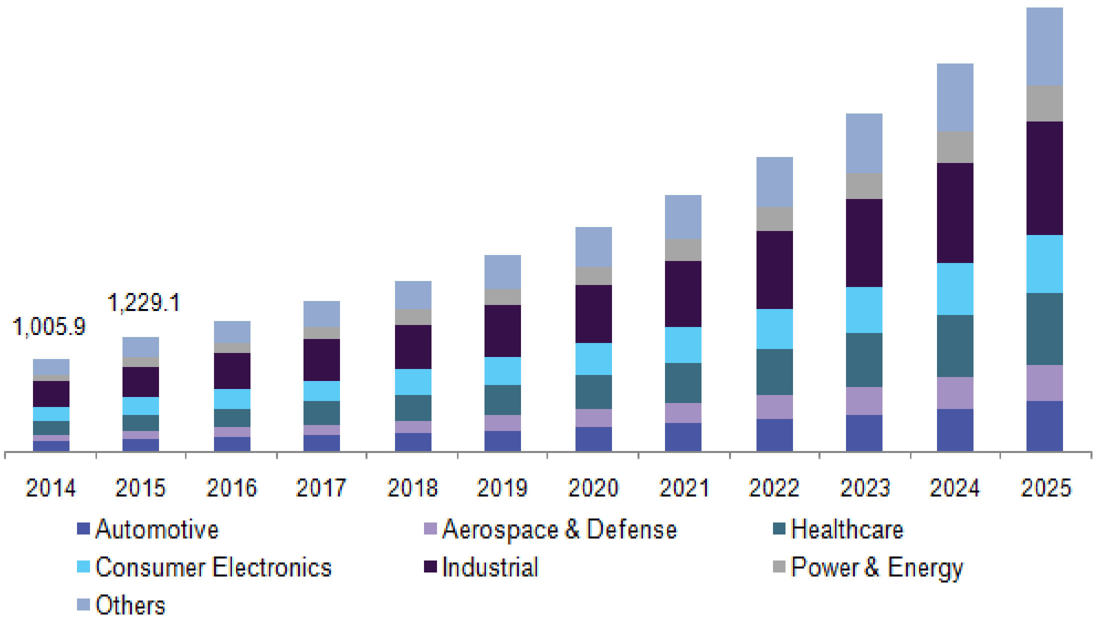


Figure 9 Global 3D printing technology growth in different industries (“3D Printing Market Size, Share and Trends Analysis Report” 2018).

3.4 3D PRINTING APPLICATIONS

3D printing technology has practical applications in high-tech industrial fields, such as aerospace and automotive production. 3D printing uses a wide range of materials, including metals, polymers, and ceramics to produce various products (Ankner and James 2017). The application of 3D printing in the manufacturing industry may eliminate the need to import plastic-based mold from suppliers around the world. Also, the use of 3D printing can contain costs in the process of developing a product. This technology has gained more attention in the medical field, as it can produce a wide variety of medical implants from CT-imaged tissue replicas. For a long time, product customization has been a challenge for manufacturers due to the high costs of producing unique patient-customized products (Stansbury and Idacavage 2016).

Customized functional products are currently becoming the trend in 3D printing, as predicted by Wohlers Associates, who envisioned that about 50% of 3D printing would revolve around the manufacturing of commercial products in 2020 (B. Berman 2012). The ability to print parts directly could have significant implications for businesses, the military, and construction. The military especially needs to maintain large inventories of spare parts on ships, foreign bases, and the battlefront. The US Army has begun printing surgical instruments, battlefield parts, and protective masks directly in war zones. The US Navy installed 3D printers on ocean-going vessels to train sailors to print and assemble the required drones on demand (Cunningham, Schrader, and Young 2015). Likewise, 3D printing is used successfully to construct cheap houses ($4,800) in Shanghai, China by WinSun group in less than a day (Wu, Wang, and Wang 2016). For now, additional sectors such as educational development, consumer electronics, and architecture are motivated to get the benefit of using 3D printing technology.

3.4.1 Aerospace components

In the aerospace industry, AM is considered one of the most promising way to produce spare parts and components. The aerospace 3D printing market is projected to grow from $0.7145 billion in 2017 to $3.0579 billion by 2022 ("Aerospace 3D Printing Market by Vertical - 2022" 2017). The 2018 Wohlers report, states that metal AM has been growing dramatically to reach 21% of overall aerospace industry growth and to exceed $7.3 billion ("Wohlers Report, 3D Printing and Additive Manufacturing" 2018). By contrast, conventional manufacturing of aircraft parts involves very long lead times and a very high cycle service to meet customer demands. Thus, those circumstances place a heavy burden on the aircraft industry to maintain a high level of safety inventory and costly supply chain (Liu et al. 2014).

The aerospace industry uses advanced materials such as super-strong nickel-chromium-based alloys that are quite difficult to machine in the Computer Numerical Control (CNC) machines and produce a lot of waste material. Therefore, using AM reduces waste material significantly, down to around 10% to 20% (Campbell et al. 2011). The 3D printing process can print objects on demand in remote locations; this benefit enables astronauts to print their tools and replacement parts in space. NASA has shipped 3D printers to the International Space Station (ISS) to manufacture parts as needed immediately (Liu et al. 2014). This decreases the need to ship and store spare parts, thus circumventing the weight restrictions on spacecraft (Attaran 2017b). AM offers the ability to redesign parts to meet new needs, or to reduce multiple pieces to a single multi-functional component or simply to fewer parts. This has paved the way for designers to create complex shape parts that are necessary for integrated functions, i.e., structural, heat dissipation and airflow would be very difficult to make on conventional machines. For example, GE Aviation has developed a housing for the compressor temperature sensor with optimized geometry

(Kellner 2015) as shown in Figure 10-a. Likewise, the Airbus Group EADS (European Aeronautic Defence and Space Company) replaced the standard Airbus A320 nacelle hinge bracket of cast steel by a 3D printed titanium bracket with optimized topology as shown in Figure 8-b. The bracket's weight is reduced from 2.033 kg to just 0.327 kg without sacrificing strength, and in the same time the energy consumption and CO_2 emissions are reduced by nearly 40% over the full lifecycle (Hessman 2015).

Figure 10 The 3D printed metal parts for (a) housing for compressor inlet temperature sensor of GE jet engines (Kellner 2015), (b) Airbus A320 nacelle hinge bracket (Hessman 2015).

Today, engineers can make fully-functional components that have composite shapes with different metal alloys using metal AM. The AM products are featuring material properties that are equivalent to counterparts that are traditionally manufactured. SpaceX designed and built the SuperDraco rocket engine using metal AM technology as shown in Figure 11. The combustion chamber of the SuperDraco space engine is regeneratively cooled, and it is manufactured from superalloy which is hard to machine in CNC (Mouzakis 2018).

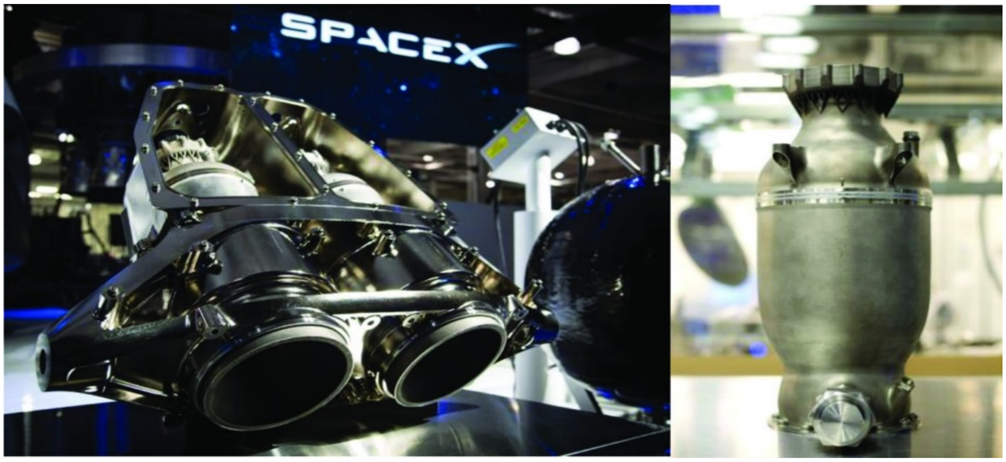


Figure 11 SPACEX, Superdraco engine (Mouzakis 2018).

Moreover, with 3D printing, it is possible to simplify parts by combining multiple components and decrease the part's weight that result in reduced fuel consumption. GE produces 3D printed nozzles weighted 25% less than the ordinary nozzle as shown in Figure 12 (Kellner 2015). GE invested $22 billion in AM technology to produce engine nozzles in mass-production (Columbus 2015). As a result, AM allows engineers to replace complex assemblies with single parts that are lighter than previous designs, saving weight and boosting a jet engine's fuel efficiency. Furthermore, 3D printing technology adapts the concept of design for manufacturing to the manufacturing of the design. This enables manufacturers to profitably fabricate the personalized design that the customer desires and values highly.

Figure 12 The LEAP engine (a) has 19 3D-printed fuel nozzles (b) (Mouzakis 2018).

3.4.2 Automobile components

In the automotive sector, many manufacturing companies have successfully implemented 3D printing technology in their manufacturing processes. 3D printing can be integrated with the automotive assembly line to make car parts, components, and prototypes. Rapid prototyping is still the most attractive application of AM processes (Saunders 2018). Currently, direct metal AM technology is not suitable for mass production of automotive parts. However, binder printing is gaining full acceptance to produce a sand mold, or plastic pattern as shown in Figure 13. The casting of large complex components using a 3D printed sand mold can save development time and allow for multiple design iterations during the prototyping cycle (Duda and Raghavan 2016). Ford Motor Company has increased the total investment in its Kentucky Truck Plant to $925 million using 3D printing technology to increase the production of vehicles by 25%. Constructing a prototype part using traditional manufacturing processes may cost over $250,000 just in tooling, and take 8 to 16 weeks, while it can be done with a 3D printer in just hours or days, and cost only to a few thousand dollars (Saunders 2018). As a result, 3D printing technology can make sense for production specific customized and complex casting applications with high quality.

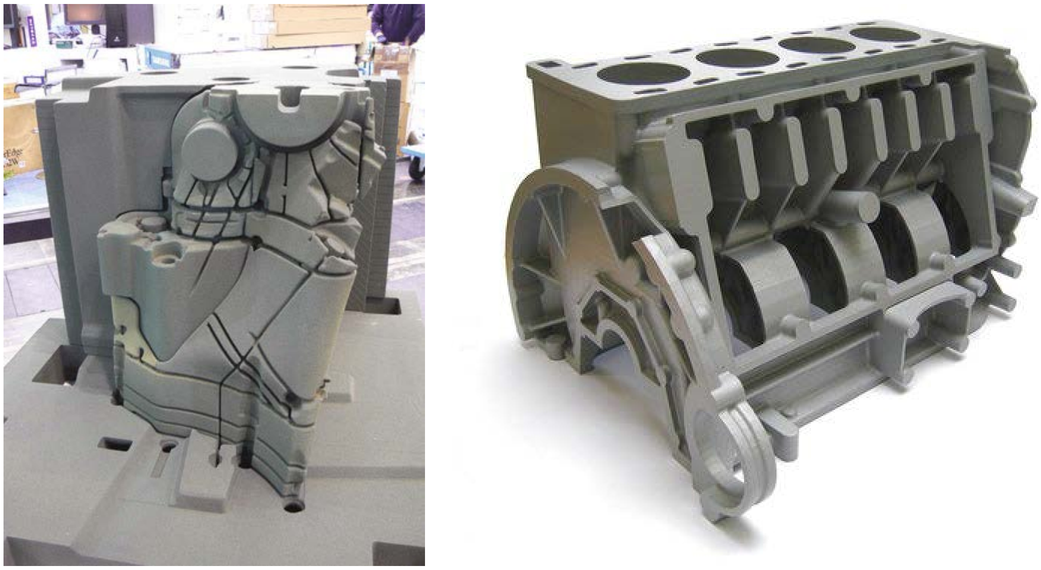


Figure 13 3D printed silica sand mold for casting an aluminum Formula-1 transmission housing (a) 3D printed plastic pattern for investment casting(b) (Contract Manufacturing Services 2016).

3.4.3 Life science

3D printing is widely used in healthcare to reduce surgery time and the risk of post-operative complications, thereby improving patient experience and quality of care. It is estimated that, by 2019, use of 3D printing will be a critical tool in individualized healthcare. It is predicated that over 35% of all surgical procedures requiring 3D printed devices such as prosthetic and implant. In the developed world, up to 10% of people will be living with 3D-printed items on or in their bodies (Basiliere 2015). 3D printing is used to fabricate different custom implants such as prosthetics, reconstruction bones, hip joints, and skull implants. Metal AM process has been applied to make orthopedic implants of advanced materials to replace the hip joint (Sing et al. 2016). Figure 14 shows the key steps of the processes including the powder deposition, energy source, and the final part.

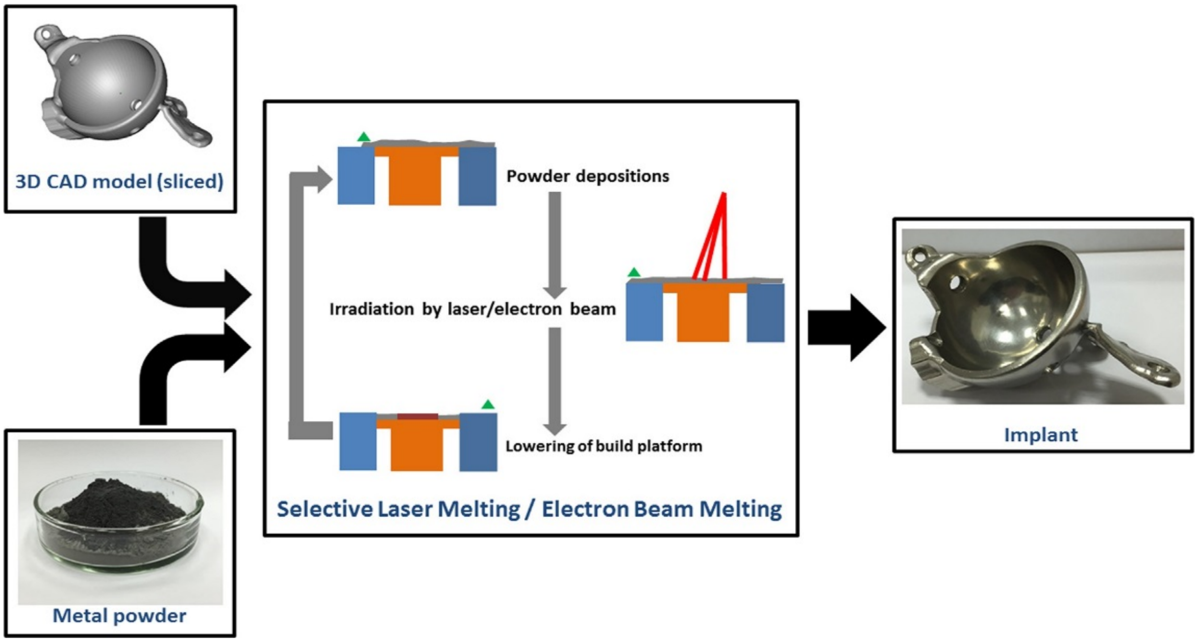


Figure 14 Key steps of fabricating an implant in metal AM process (Sing et al. 2016).

NextDent is a specialized company that produces personalized dental crowns using 3D printing technology. The teeth can be 3D scanned and then printed in a resin to ensure that the dental crown is accurate aesthetic and functional fit for the patient. (Chung et al. 2016). In the orthopedic realm, a patient's feet can be scanned and the file transmitted online to produce 3D printed custom orthotics (Özceylan et al. 2017). AM techniques have wide application in the medical field and this is expected to increase significantly in the future. More research is needed to develop medical devices of different biomaterials that will meet patient's needs.

3.4.4 3D printed building

Additive manufacturing technology has expanded into the construction industry to reduce construction time and workforce. In recent years, researchers have combined robots and 3D printing extrusion nozzles to build houses, bridges, furniture, even automobiles (Langnau 2016). The contour crafting method is used with a larger nozzle and high pressure to extrude a concrete paste to construct building structures. The method includes a designed trowel that is attached to the printhead, to have a smooth finish instead of a layer-by-layer appearance (Khoshnevis 2004).

The 3D printing extrusion nozzle can build remarkable objects. The “Office of the Future” was constructed in China (Killa Architectural Design 2016), then shipped to the Dubai Future Foundation in the UAE, see Figure 15. The 3D printed office is a fully functional building featuring electrical, water, telecommunications, and air-conditioning systems. The project ultimately reduced labor costs by 50% to 80% and construction waste by 30% to 60% (Wu, Wang, and Wang 2016).

Figure 15 3D printed office of the future in Dubai (Killa Architectural Design 2016).

ProMIT researchers designed a system that consists of a tracked vehicle that carries a large industrial robotic arm, which is ended by a small precision-motion robotic arm. The system can print the basic structure of an entire building faster and less expensively than traditional construction methods. Also, the building structure could be customized or entirely modified to the needs of the site. Furthermore, material properties such as density can be adapted to provide optimum combinations of strength and insulation (Chandler 2017). Thus, this approach enables to design and construct new kinds of buildings that would not be feasible with traditional building methods.

At this moment, 3D printing of concrete is going through rapid development, and it holds the promise of changing the landscape of construction (Kothman and Faber 2016). 3D printing of concrete can improve the performance of manufacturing by shortening the lead time and reducing material waste. This reduce the number of production steps, simplifying logistical and production efforts (Kothman and Faber 2016). The new concrete slab building created by 3D printing foretells the possibility of producing concrete highway slabs. 3D printing technology eliminates the mold manufacturing method, and the product can be made locally, thereby reducing the distance required to ship the finished products to market.

3.5 TRANSPORTATION INFRASTRUCTURE DESIGN

3D printing technology empowers transport decision makers to design structures and facilities at less cost. Outdoor structures such as small bridges and bus shelters could be manufactured and designed to fit into the environment without losing integrity and safety. The world’s first 3D printed pedestrian bridge of micro-reinforced concrete has been constructed in the urban park of Castilla-La Mancha, Madrid, see Figure 16. The project is 12 meters long, and 1.75 meters wide (Martin 2017).

Figure 16 The world’s first 3D printed pedestrian bridge (Martin 2017).

Recently, technology startup MX3D constructed a steel pedestrian bridge using a 3D printer and six-axis robots, see Figure 17. The bridge is 12 meters long and 4 meters wide. It will eventually cross a canal in the Dutch capital in Amsterdam. 3D printing and robotic technology allowed the structure to be constructed at the site, and in mid-air (Block 2018).

Figure 17 MX3D 3D printed constructed a steel bridge (Block 2018).

As 3D printing technology keeps advancing and developing, companies and consumers can use a greater variety of materials to produce larger-scale and more complex, ambitious projects. 3D printing holds the potential for new approaches and solutions to existing transportation issues.

4 CHALLENGE TO TRANSPORTATION

AM technology can create a gradually diversified array of products, eliminate critical segments of the supply chain, cluster production and delivery service (Ankner and James 2017). It can change inventory and logistics systems by simplifying the supply chain. The structural changes from 3D printing will affect the ways in which all transportation is planned, managed, and financed. Figure 18 shows the suitability of products for 3D printing and the transportation cost rates (Coetzee 2015). Thus, the costs of distribution, assembly, inventory, and transmitting the products can be affected significantly. It requires the transportation community to act decisively to plan for transportation investments, management development, and the organization of the infrastructure design.

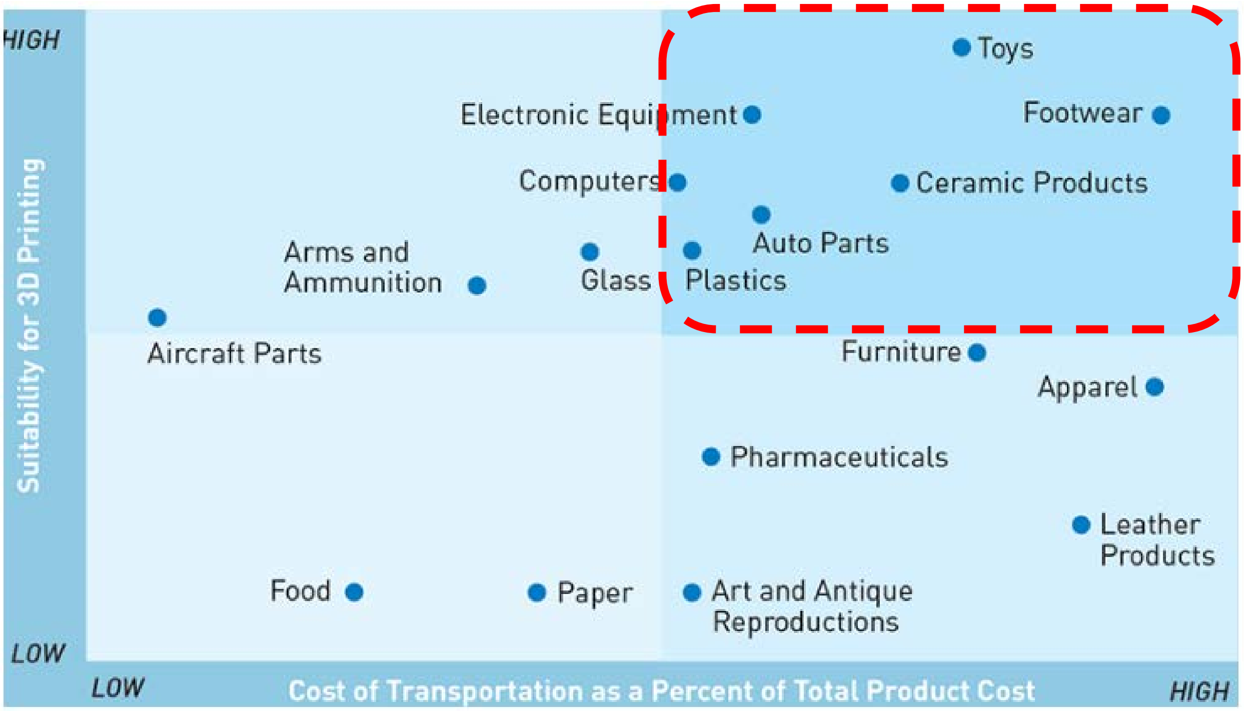
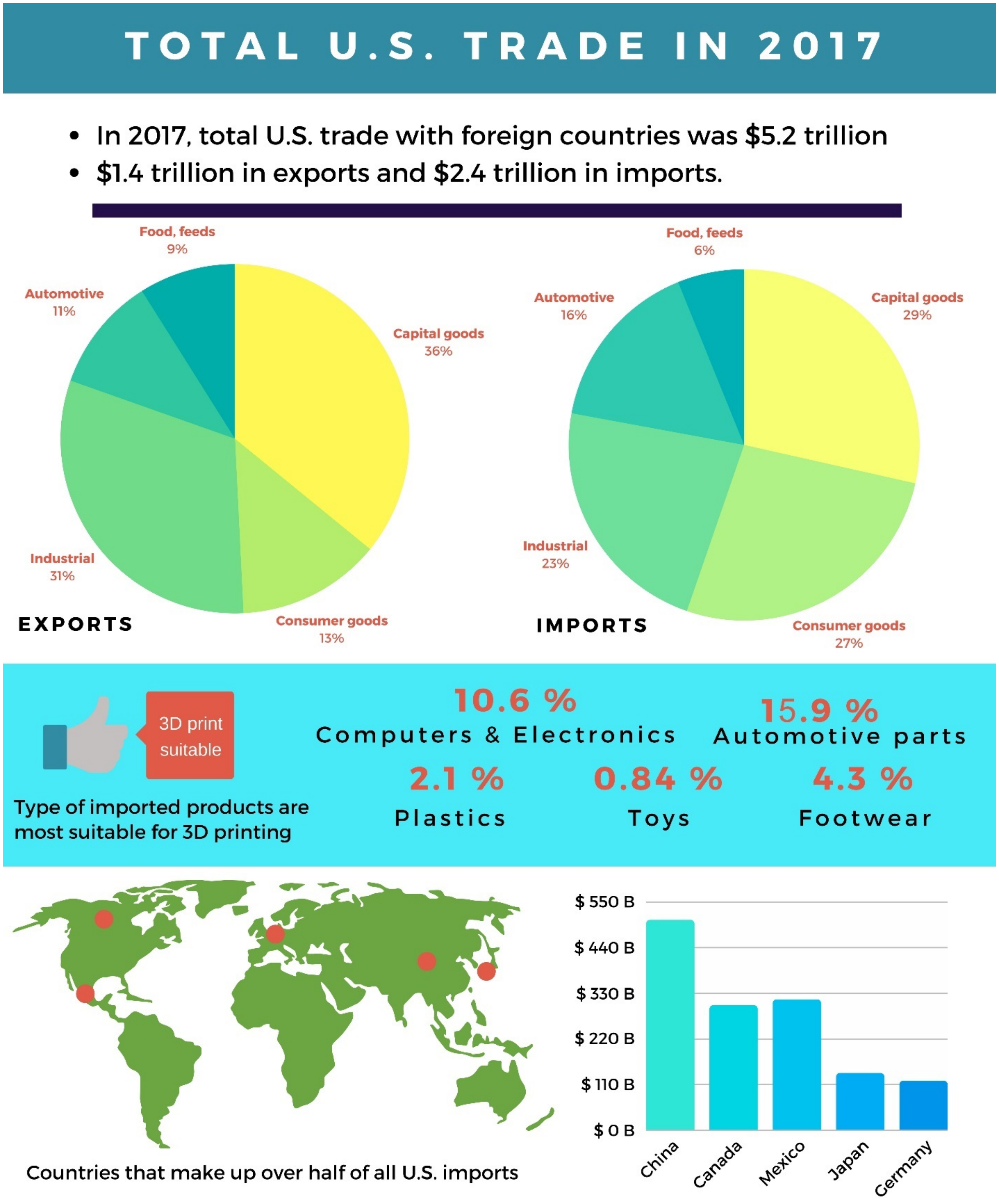


Figure 18 Shows suitable products for 3D printing versus the transportation's cost (Coetzee 2015).

Figure 18 shows highly suitable products for 3D printing, including auto parts, computers, toys, footwear, and plastics. These products also have high transportation and warehousing costs, relative to the total production cost. The balance report stated that the total US trade with foreign countries was $5.2 trillion for both goods and services in 2017 (Amadeo 2018). Goods contribute $1.4 trillion in exports and $2.4 trillion in imports, as shown in Figure 19. The imported goods that are suitable for 3D printing technology include automotive and engine parts at $359 billion, computer equipment at $256 billion, toys at $20 billion, and footwear at $123 billion, and plastics at $34 billion. It is noteworthy to consider the powerful disruptive effects of 3D printing on the supply chain for these products, if they are to be manufactured locally to their markets. When these products are fabricated locally using 3D printing near to customers, the freight movement and the number of trucks can be reduced, as well as the maintenance cost of infrastructure. For instance, the US government spent $221.3 billion for highway-related purposes in 2012. The outlay included $105.2 billion for improvement to highways and bridges, $54 billion for routine maintenance, and the remainder for services, administration, and safety of highways (Status of the Nation's Highways, Bridges, and Transit 2013). In conclusion, beneficial savings in the maintenance cost of highway and bridge infrastructure can be achieved.


TOTAL U.S. TRADE IN 2017

- In 2017, total U.S. trade with foreign countries was $5.2 trillion
- $1.4 trillion in exports and $2.4 trillion in imports.

Type of imported products are most suitable for 3D printing

Countries that make up over half of all U.S. imports

Figure 19 The total U.S trade in 2017.

4.1 SUPPLY CHAIN

Logistics of the supply chain is likely the first large-scale business that may be affected by 3D printing technology. 3D printing can be disruptive to the global setup of the supply chain by eliminating or reducing the need for high volume facilities, construction distribution, and low-level assembly lines (Attaran 2017b). Figure 20 illustrates changes in the supply chain that occur through the application of 3D printing.

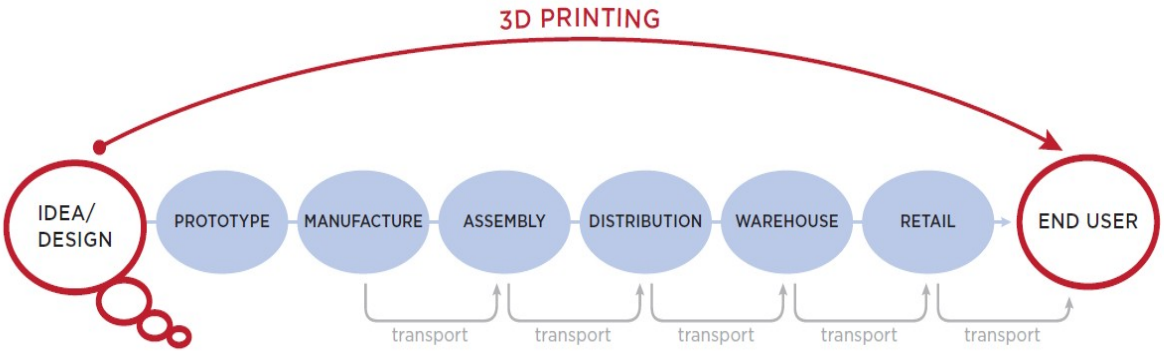


Figure 20 Traditional versus 3D printing supply chain (Özceylan et al. 2017).

In traditional manufacturing processes, raw materials are usually imported and shipped from several suppliers to centralized factories that fabricate and assemble the final product (Baby 2017). On the contrary, the 3D printing process enables companies to decentralized production concepts to produce a complex shape and various products using a single 3D printer. Figure 21 provides a global view of the vast differences between traditional and 3D supply chains.

Traditionally, the finished products are stored in warehouses, and then the inventory is delivered into markets where there may be uncertain and changing demand, and the associated risk of creating stockpiles of unwanted products (Sulavik 2016). With 3D printing, there is no need to stack the finished product on shelves or in warehouses, because the products can be printed on demand using AM technology.

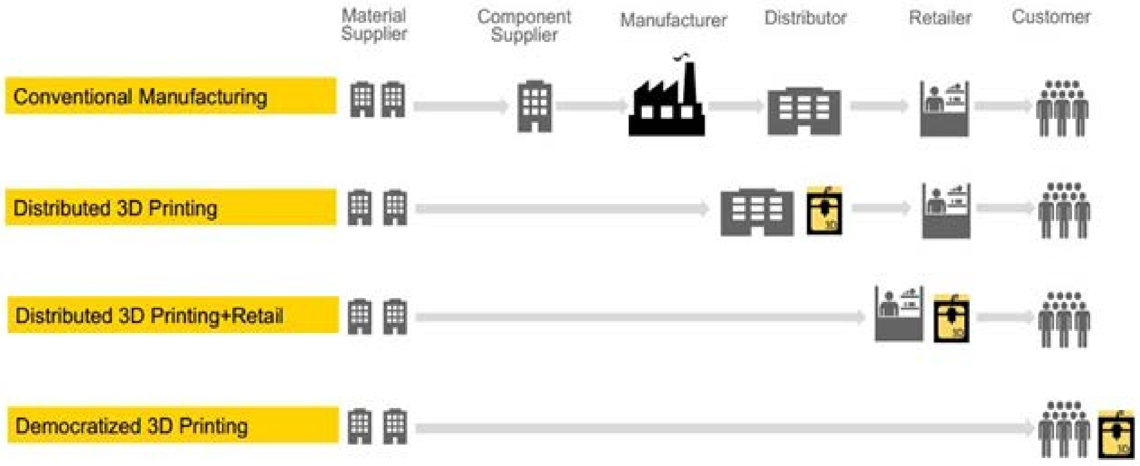


Figure 21 The global view of vast differences between traditional and 3D supply chains (Baby 2017).

The 3D printing supply chain is pulled by a customized product that is locally printed, and then distributed directly to the customer. As a result, production chain steps such as lead time, assembly lines, and time to market are reduced. This yields significant economic savings in logistics and production costs (Liu et al. 2014). Moreover, AM techniques become more agile and better able to react quickly to customer demands.

Some take the view that 3D printing is not conducive to mass production because the cost per unit is higher and production time slower than using traditional manufacturing processes (Kubáč and Kodym 2017). However, the 3D printing cost may be lower when one considers the overall supply chain costs. The cost is the same for each unit produced by the AM process, while the cost is reduced as quantities increase by the traditional manufacturing process as shown in Figure 22.

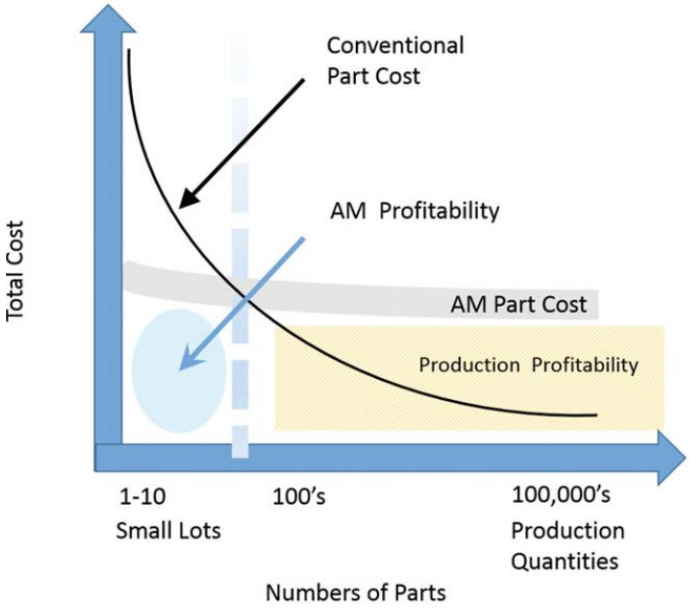


Figure 22 Customized cost for a low number of products (Attaran 2017a).

4.2 FREIGHT BUSINESS

Freight transportation typically represents the most significant cost component of the logistics cost for manufacturers, distributors, and retailers. In 2017, US transportation costs reached $945 billion. Every day, approximately 50 million tons of freight moves across the country (Monahan et al. 2018). A growing manufacturing sector results in increased freight movements and freight costs that involve line haul, fuel, and accessories. 3D printing technology has a significant potential to alter decades old goods movement patterns and to enable organizations to bypass the traditional supply chain (Özceylan et al. 2017). Freight companies around the world are aware that 3D printing could disturb the freight core business by lowering shipping volumes. Port traffic and long-distance distribution are likely to be reduced, causing a decline in the cargo industry, as more materials for 3D printing can be produced domestically. If parts can be manufactured when and where they are needed, this will also affect high value and urgent cargo levels (Garrett 2014). According to a report of Strategy & Business in 2015, almost 41% of air cargo and 37% of ocean container shipments could be threatened by 3D printing, along with 25% of trucking freight business (Rothfeder 2015). Therefore, the need for both high volume production facilities and low-level assembly workers can be eliminated (Kubáč and Kodym 2017). It is not financially efficient to send a product across the globe when it can be fabricated almost anywhere at the same cost or lower. So, the demand for local production sites that are closer to consumer markets will increase. Initially, this would mean a decrease in long-distance shipping and an increase in last mile shipping and smaller truck activities (Villanueva 2015). An MIT study indicates that the adoption of 3D printing can reduce supply chain costs by 50% to 90%, with this being particularly true for slow-moving and custom products. The bulk of the savings for traditional manufacturers would come from the reduction of transportation activity and worldwide goods transfers (Bhasin and Bodla 2014).

AM technology could replace the complicated global supply chain with a new economy based on a high-tech system of connected suppliers. The design and prototype of 3D printing are digital files that can be sent faster and more efficiently anywhere to print it out as a final product, skipping many traditional manufacturing steps (Villanueva 2015). These will challenge many long-term strategic plans for ports, and financing for new or expanded facilities and intermodal connections to meet U.S. demand. It may alter congestion management plans. As a result, traditional transportation planning is required to adopt the current logistic strategies when the 3D printing technology moves closer to end users.

4.3 WAREHOUSING

Warehouses and distribution centers (DCs) are primarily used for temporary storage, possible modification, customization, and distribution of goods. They are located at or near airports and ports to support cargo operations (A. Strauss-Wieder, Inc. 2001). In 2017, the total US inventory carrying cost was $428 billion, including warehousing, financial cost, insurance, and handling (Monahan et al. 2018). It is costly for companies to store produced parts in warehouses with no guarantee that all parts will ever come into use. For example, aircraft spare parts have very high inventory cost, estimated to be $400,000 per aircraft per year (Partanen et al. 2010). Likewise, the US military in 2009 spent $194 billion on its logistics and spare parts supply chain management. Furthermore, the US military maintained inventory of approximately 4.6 million spare parts, valued at $94 billion (Khajavi, Partanen, and Holmström 2014).

With the ability to print parts on demand, there will no longer be a need for finished products to be stacked physically in warehouses. Thus, even with small improvements, these spare parts can be printed and rapidly delivered to the customer with fewer logistics operations. Instead of keeping all the possible spare parts at or near the site where they might be needed, the deployment of printers and raw material would produce various spare parts and reduce the cost as well. With 3D printing, the necessary inventory shifts to the raw materials (e.g., powders or filament coils) rather than semi-finished parts and components. The handling of these raw materials is cheaper, safer, and requires fewer skilled workers (Mohr and Khan 2015).

3D printing is the preferred process when custom parts, or low-volume production, are needed (Birtchnell and Hoyle 2014). Across the entire supply chain, especially for slow-moving and customized products, using 3D printing enhances the potential cost savings in the range of 50%-90% (Ankner and James 2017). However, to achieve efficiency in lead-time reduction and mass production of products, the output should decentralize by using a dense network of 3D printers near to the source of demand rather than producing at one factory (Khajavi, Partanen, and Holmström 2014). These printers can be in regional warehouses or local distribution centers to produce individualized parts.

Today's consumers lead busy lives, and it is more stressful and time-consuming to drive to traditional brick and mortar shops. Also, worldwide urbanization is continuously increasing, so customers will increasingly live in cities. Since regulatory fees and tolls are steadily growing, especially in large cities, the transport costs are gradually increasing as well (Muller and Karevska 2016). Logistics providers support companies to create a virtual warehouse where digital files of spare parts are stored in software databases securely. Kazzata organization developed and implemented the concept of the virtual warehouse to provide an online marketplace for users by establishing a CAD repository for obsolete and rare spare parts (Chung et al. 2016). When a component is required, the customer can search for the right part and send the file to be additively manufactured at a 3D printer anywhere.

In conclusion, 3D printing can decrease the need for large inventories and it can improve the ability to repair and replace equipment parts quickly. Thus, locating small distribution hubs near to significant consumer clusters (e.g., large cities) can save transport costs and provide for the swift delivery of products. Such centers mean the last-mile logistics is essential for shipping and supplying actions.

4.4 RETAIL AND CARRIER COMPANIES

Although the 3D printing poses a threat to disrupt packaging and handling business, it also presents opportunities for market growth driven by trends favoring product customization, rapid fabrication, and quick delivery. Leading retail companies as well as supply chain providers are already developing local 3D printing manufacturing centers and local delivery networks.

Amazon is well-known for its interest in delivering goods directly to customers within the shortest timeframe possible. To this end, they located their warehouses in locations close to major metropolitan areas to reduce delivery schedules. Amazon is experimenting with the use of drones to circumvent supply chain delivery impediments. In February 2015, Amazon filed a patent application concerning equipping trucks with 3D printers, so the product can be printed on demand while it is delivering to the customer's doorstep (Apsley et al. 2018). A comparative illustration of traditional and automobile 3D printing of Amazon is shown in Figure 23. The system would help speed up the delivery process even further and help to reduce the warehouse space (Özceylan et al. 2017). As a result, successful development of mobile printing capabilities will eliminate another step between the consumer and the product supplier.

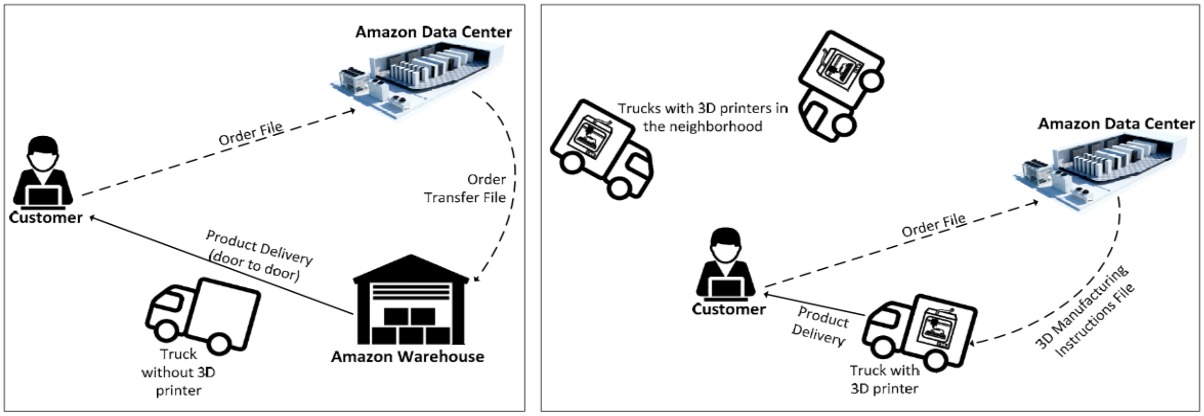


Figure 23 Schematic of automobile 3D printing provider (Özceylan et al. 2017).

United Parcel Service (**UPS**) invests in AM technology to take advantage of these trends by making 3D printing service available in UPS stores nationwide to print full-scale parts on-demand. UPS would manufacture and deliver the requested product on a short schedule to anywhere in the US (J. Berman 2016).

United States Post Office (**USPS**) has created a new business opportunity out of the potential threat that 3D printing poses to its small packages operations. USPS local offices can be used for material storage and printing as well as delivery products; the customers can send design files to be printed there (Shavin 2018). USPS estimates that the service model with 3D printing hubs could increase its commercial package revenue by $646 million (Columbus 2015).

4.5 TRANSPORTATION AND MANUFACTURING JOBS

3D printing may cause a significant shift in transportation and logistics handling jobs, and reduce the need for labor (Campbell et al. 2011). Moreover, 3D printing produces cost savings by removing low labor cost, assembly lines and long-distance shipping of products ("3D Printing and the Future of the US Economy" 2014). These are offset by sharp reductions in transportation and logistics handling as shown in Figure 24. The shifts in transportation logistics disturb the need for the financing of the primary port and intermodal capital projects that dependent on increasing overseas supply chain goods and traffic (Ankner and James 2017).

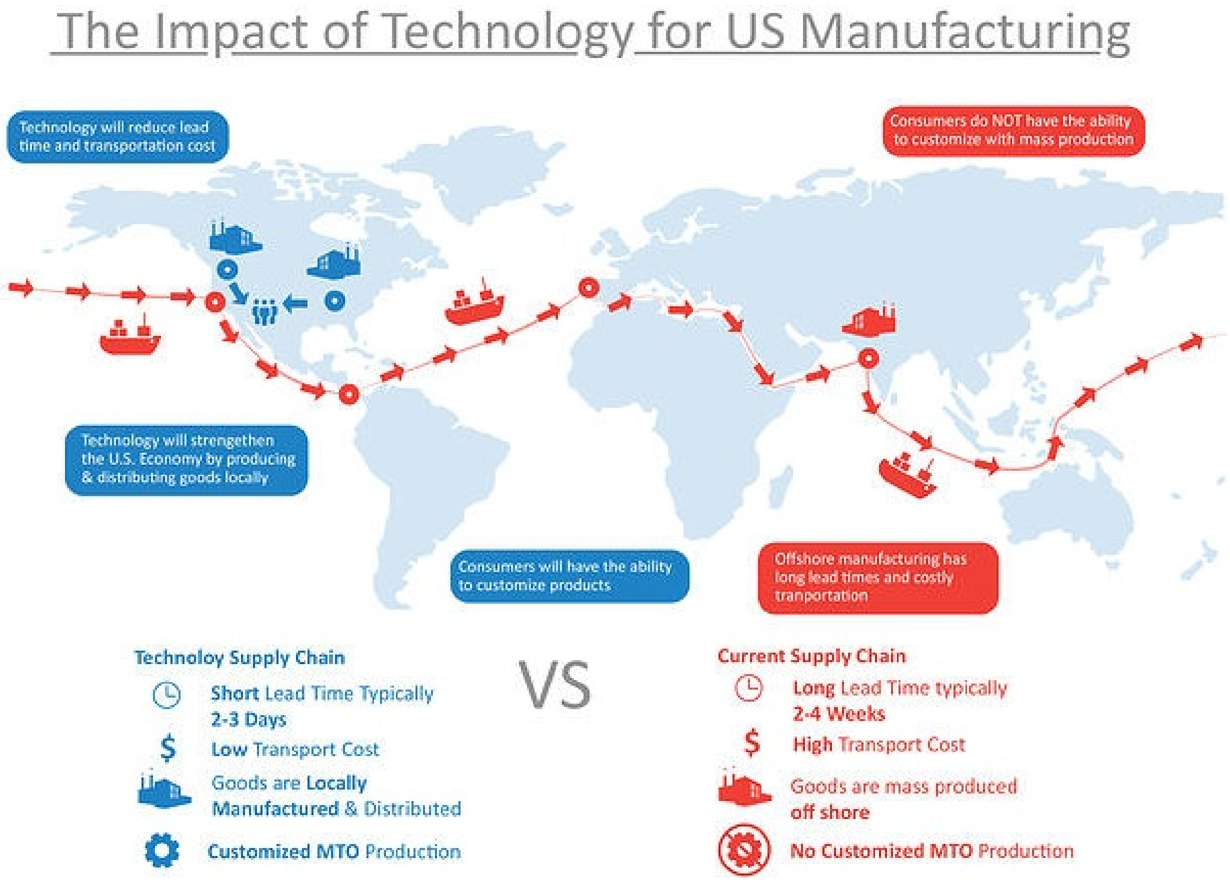


Figure 24 Expected supply chain ("3D Printing and the Future of the US Economy" 2014).

According to the federal Office of Trade and Economic Analysis, the level of employment supported by transportation and related occupations was projected at 10.7 million jobs in 2016, see Figure 25 ("Jobs Supported by Exports 2016" 2017). It seems that transportation jobs will decline as a result of widespread 3D printing technology within the next decade or two. Part of the net decline in jobs will come from the use of autonomous freight vehicles, and drones to facilitate 3D product and general consumer deliveries. On the other hand, manufacturing jobs will shift around the world to places where 3D printing technology is involved. Currently, the US manufacturing sector is projected at 12.4 million jobs. Due to labor costs, much of US manufacturing has been outsourced overseas. But it is expected that 3D printing would bring jobs back home and grow manufacturing jobs by 20%. (HP and Kearney 2018). The US has high consumption and a good manufacturing economy, so there is the potential for 3D printing to create more new jobs.

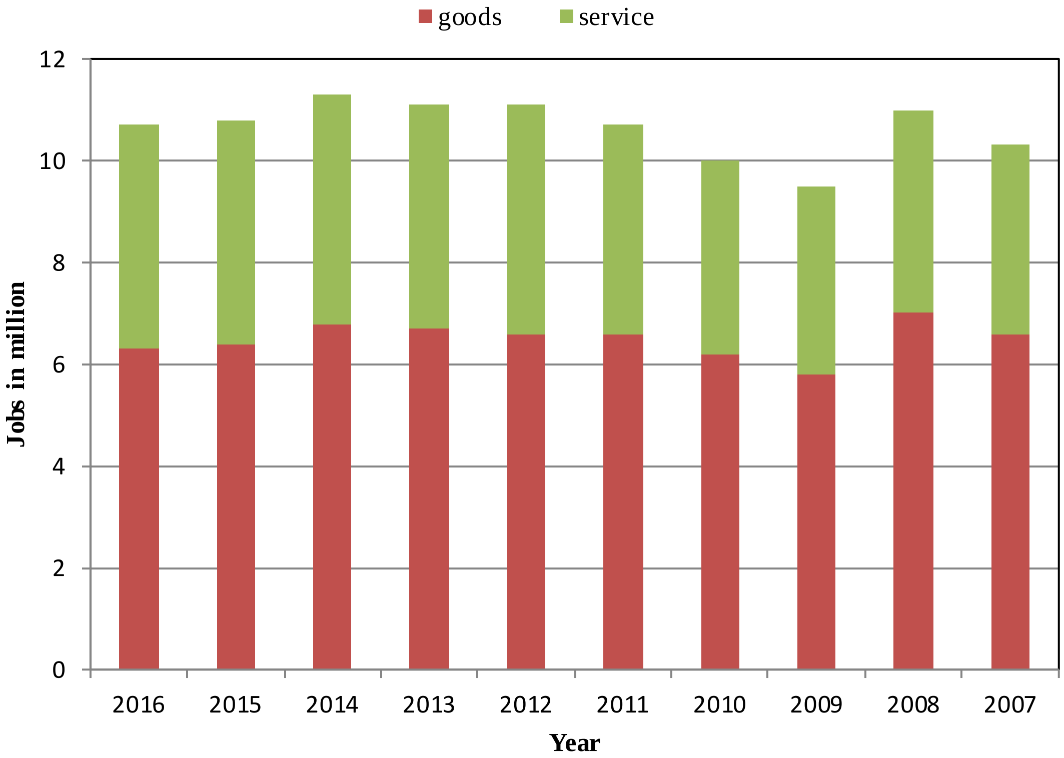


Figure 25 Shows number of Jobs supported by goods and services exports in the US.

AM could affect the exporting markets in countries like China, Japan, and Germany that have built their prosperity on export-led growth (Campbell et al. 2011). The demand for imported consumer products could experience a relative decline, as more production is shifted to consumer countries. However, countries with large domestic markets such as China, India, Indonesia, and Brazil, may successfully take advantage of AM economy without a reduction in prosperity (Campbell et al. 2011). Companies that have superior product designs would export the models to be printed in 3D printing facilities in the target country, thus maintaining profits but reducing the movement of physical goods among nations. At current, companies that have capabilities to capitalize on 3D printing are available in the US, and the demand for 3D printing products is growing ("3D Printing and the Future of the US Economy" 2014). Thus, there is hope that 3D printing may bring more jobs opportunities home and strengthen the domestic economy.

4.6 HYBRID ADDITIVE/SUBTRACTIVE SYSTEMS

The integration of AM processing with subtractive manufacturing processes is another area of technology development promising that helps existing companies and machine shops to gain economic benefits (Strong et al. 2018). By centralizing AM resources, companies and machine shops do not have to directly invest in expensive AM systems and associated training, maintenance, research and development efforts. A recent survey reveals that 38% of companies expect to use 3D printing technology in their production line within five years without replacing traditional manufacturing processes completely (Muller and Karevska 2016). 3D printing is likely to complement traditional manufacturing techniques, as part of a hybrid approach, rather than entirely replacing them. Simply put, most metallic AM products may require more sequential post-processing to achieve the final part specifications. Thus, the need for finishing and nontraditional post-processing of metal AM parts is widely reported (Ryan et al. 2017). The hybrid-AM offers to produce near-net final parts via AM and, subsequently, post-processed and dimensional tolerance via traditional manufacturing processes.

Many established manufacturing companies have successfully implemented 3D printing technology in their manufacturing processes, often achieving remarkable results. The BMW Group has to date integrated 10,000 3D-printed parts into series production of the Rolls-Royce Phantom to shorten production times and make more economical production. 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 (Chung et al. 2016). More recently, a study has investigated a system of strategically-located metal printing AM hubs using the North American Industry Classification System (NAICS) data to determine the optimal locations (Strong et al. 2018). The results have identified certain US counties as candidate locations for AM hubs, according to 10% demand as shown in Figure 26. Consequently, AM hubs can be integrated with existing facilities in traditional manufacturing to decrease investment cost and improve customer services.

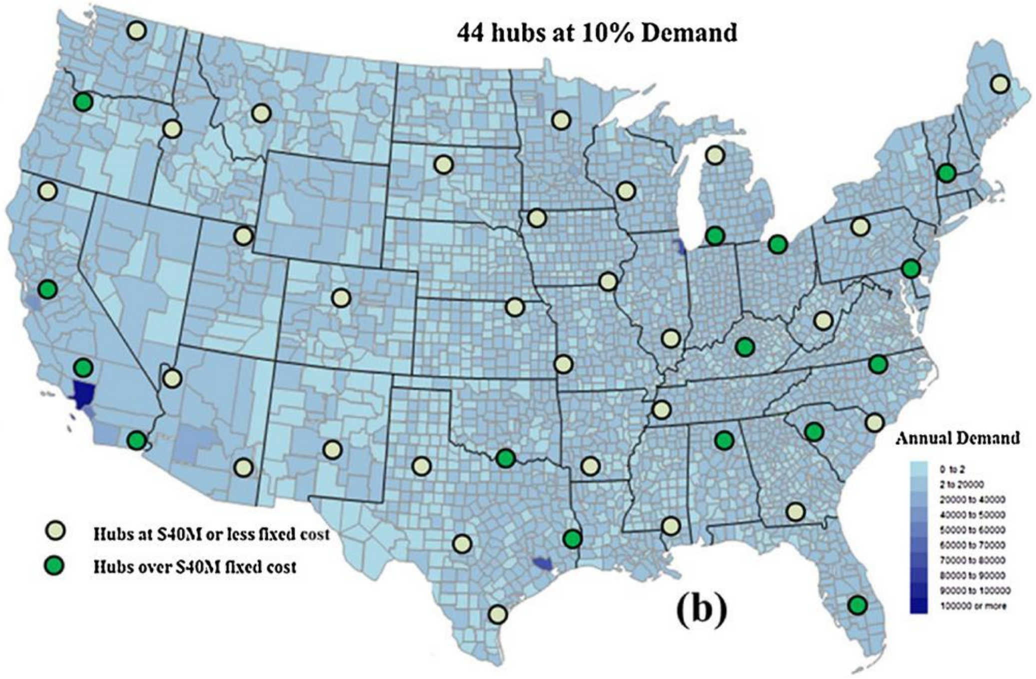


Figure 26 AM 44 hubs locations in the US at 10% demands (Strong et al. 2018).

5 FINDINGS AND CONCLUSIONS

3D printing is a promising technology that has numerous applications in various industrial segments. It paved the way to the fabrication of the personalized design products that the customer desires and values highly. There is much evidence in the accelerating growth and diversity of 3D products that a tipping point may be reached well within a decade. It is noteworthy to consider the disruptive effects of 3D printing on the transportation and the supply chains. In fact, 3-D printing could threaten 41% of air cargo, 37% of ocean container, and 25% of trucking freight business. These trends will challenge many port long-term strategic plans and current capital investments to meet US demand management plans. Therefore, transportation facilities and existing manufacturing infrastructure need to adapt, and quickly. 3D printing allows for print on demand, rendering large inventories and stockpiles of spare parts unnecessary in many cases. An MIT study indicates that the adoption of 3D printing can reduce supply chain costs by 50% to 90% this being particularly true for slow-moving and custom products. Bulk of the savings for traditional manufacturers would come from the reduction of transportation activity and worldwide goods transfers.

The developing world could be a significant beneficiary of AM production but also a loser in manufacturing jobs for export industries. Manufacturing jobs will shift around the world to places where 3D printing technology is involved. The US has high consumption and a good manufacturing economy. In 2017, the total US trade with foreign countries was $5.2 trillion, $2.4 trillion in imported goods. Over 30% of imported good are suitable for manufacture in 3D printed technology, so 3D printing may create more new jobs. Hybrid manufacturing system can integrate AM hubs with existing traditional manufacturing machine shops to decrease investment cost and improve customer services. Thus, locating small distribution hubs near to large cities can save transport costs and provide the swift delivery of products. Moreover, 3D printing would offer numerous opportunities to provide new approaches and solutions to existing transportation issues. When products are fabricated locally using 3D printing near to customers, the freight movement is reduced. Wear and tear of the infrastructure is also reduced. Thus, the maintenance cost of highways and bridges is reduced, and a reduction in vehicle emissions adds more environmental bonuses.

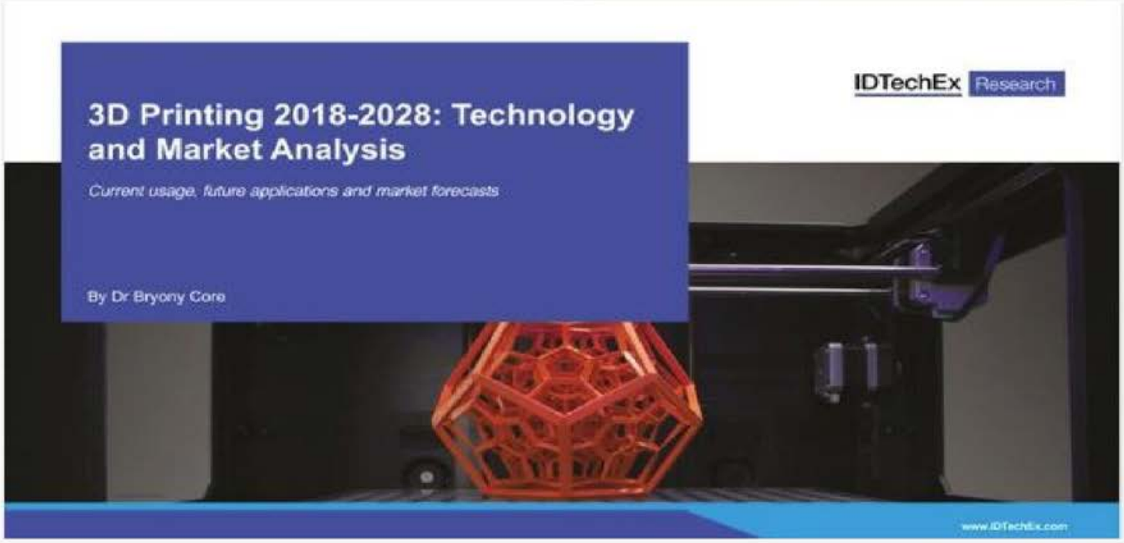
6 FUTURE WORKS

Currently, cyber security is a big challenge for 3D printing technology: how to keep design files safe? 3D printing will fundamentally change the manufacturing industry. What is the effect of 3D printing technology on traditional manufacturing jobs, and how can those jobs develop to involve a skilled work force? Is it possible to use available local materials to construct appropriate low-cost houses using 3D printing to accommodate displaced persons due to urgent catastrophes such as floods, and earthquakes?

3D PRINTING TECHNOLOGY

IN RECENT NEWS

The 3D printing market will be worth $22 billion in 2028



IDTechEx Research

3D Printing 2018-2028: Technology and Market Analysis

Current usage, future applications and market forecasts

By Dr Bryony Core

www.IDTechEx.com

IDTECHEX FORECASTS

The global market for 3D printing equipment, materials, software and services is estimated to be worth $22 billion by the year 2028.

https://www.idtechex.com/

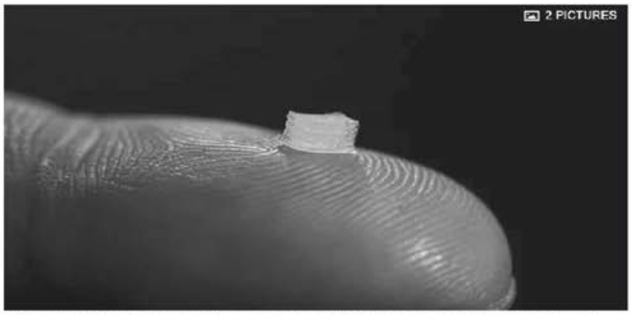
LSEV claimed to be world's first mass-producible 3D-printed electric car

Ben Coxworth | March 21st, 2018

Production on the LSEV could start as soon as next year (Credit: Polymaker)

3D-printed nerve stem cells could help patch up spinal cord injuries

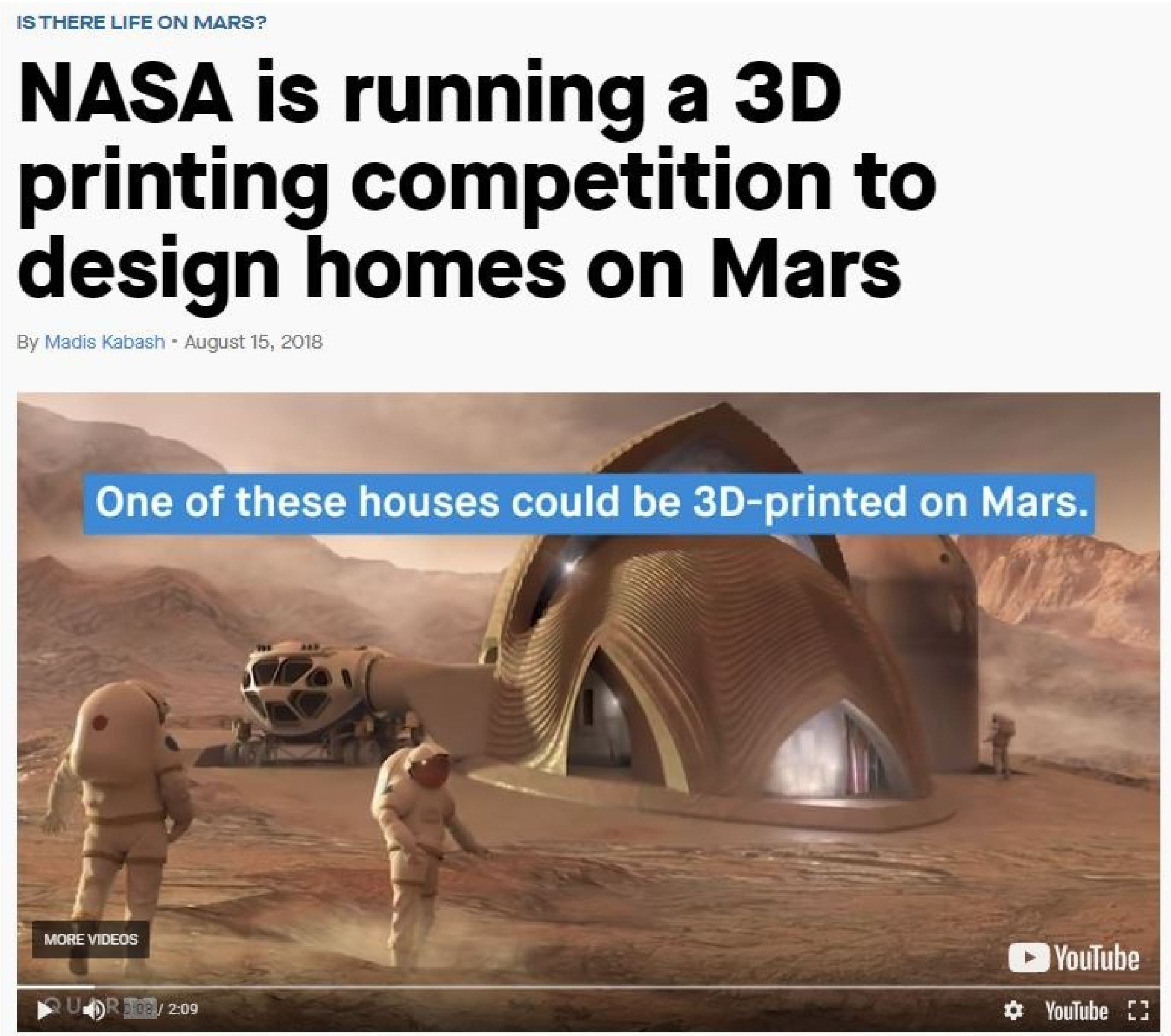
Michael Irving | August 10th, 2018



A 3D-printed device, loaded with neuronal stem cells, that can be implanted into an injured spinal cord to help "bridge" the damage (Credit: University of Minnesota)

This device is implanted at the site of a spinal injury, where the guide nurtures the stem cells until they're able to grow new nerves, connecting the undamaged cells on either side of the injury.

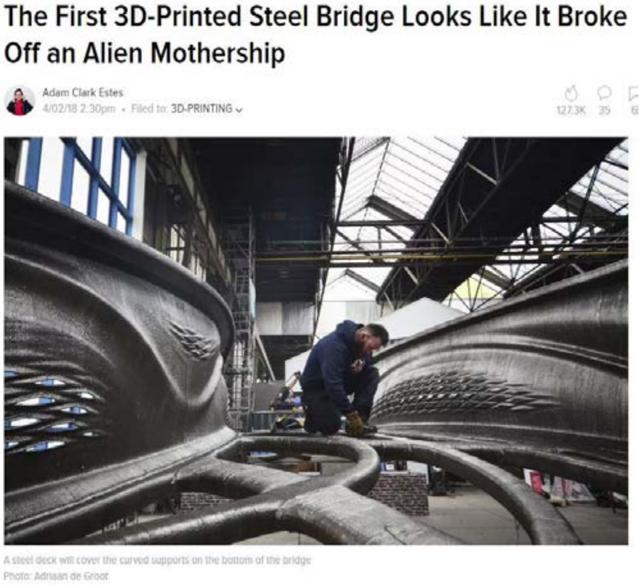
https://www.newatals.com/



IS THERE LIFE ON MARS?

NASA is running a 3D printing competition to design homes on Mars

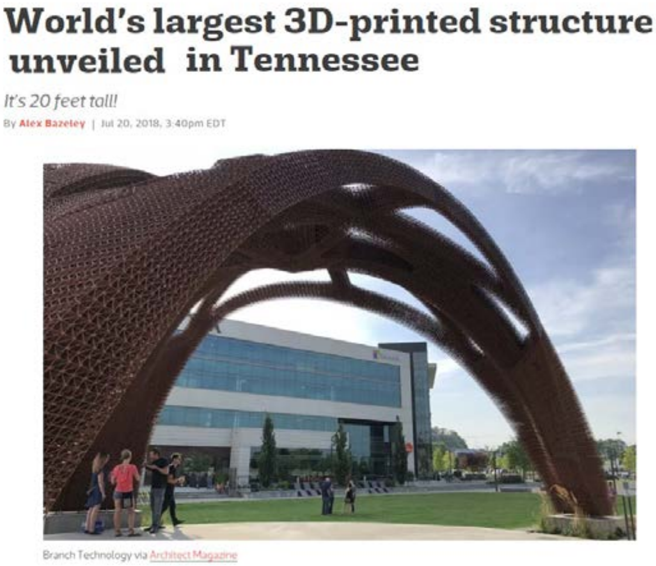
By Madis Kabash · August 15, 2018



The First 3D-Printed Steel Bridge Looks Like It Broke Off an Alien Mothership

Adam Clark Estes
4/02/18 2:30pm · Filed to: 3D-PRINTING

A steel deck will cover the curved supports on the bottom of the bridge
Photo: Adriaan de Groot



World's largest 3D-printed structure unveiled in Tennessee

It's 20 feet tall!

By Alex Bazeley | Jul 20, 2018, 3:40pm EDT

Branch Technology via Architect Magazine

7 APPENDIX I

Stereolithography Apparatus (SLA): UV light is used to initiate a chain reaction in a vat of liquid photopolymer resin (Sandeep and Chhabra 2017). The light is precisely controlled in a desired path to cure a thin layer (0.05-0.2 mm) of the resin and convert the exposed areas to a solid part (Ngo et al. 2018). When the first 2D pattern layer is cured, the platform is dipped down to allow a new layer of uncured resin to be formed. This process is repeated until the part is completed. SLA method produces parts with high level of accuracy and smooth surface finish. The schematic of SLA (CustomPartNet 2018) that illustrates the working principle is shown in Figure 27.

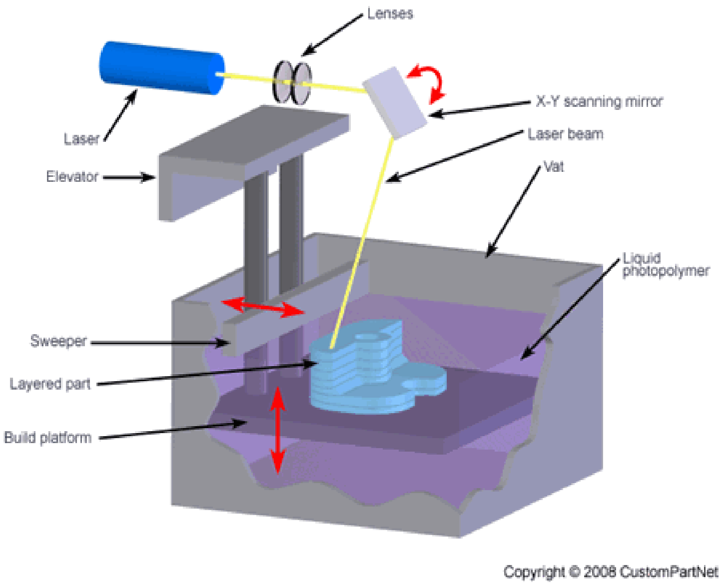


Figure 27 illustrates the working principle of SLA.

Powder Bed Fusion (PBF): Selective laser melting (SLM) and Selective laser sintering (SLS) are most common techniques of PBF process. A laser beam is used to melt and fuse many layers of powdered material selectively to form a consolidated part (Bhushan and Caspers 2017). A subsequent thin layer (0.06-0.18 mm) of powder is spread over the previous one and fused together (Ngo et al. 2018). The laser heats up the surface's temperature of powder grains; and it leads to fuse these grains together. The losing powder that surrounds the part is acting as support material for overhanging features. The surface quality and density of the printed part depends on powder size distribution and packaging, laser power, and temperature. This method is used for a wide range of materials such as plastics, metal and alloy powders (Sandeep and Chhabra 2017). PBF process is suitable for printing complex structure with high quality and good resolution. The schematic of PBF (CustomPartNet 2018) that illustrates the working principle is shown in Figure 28.

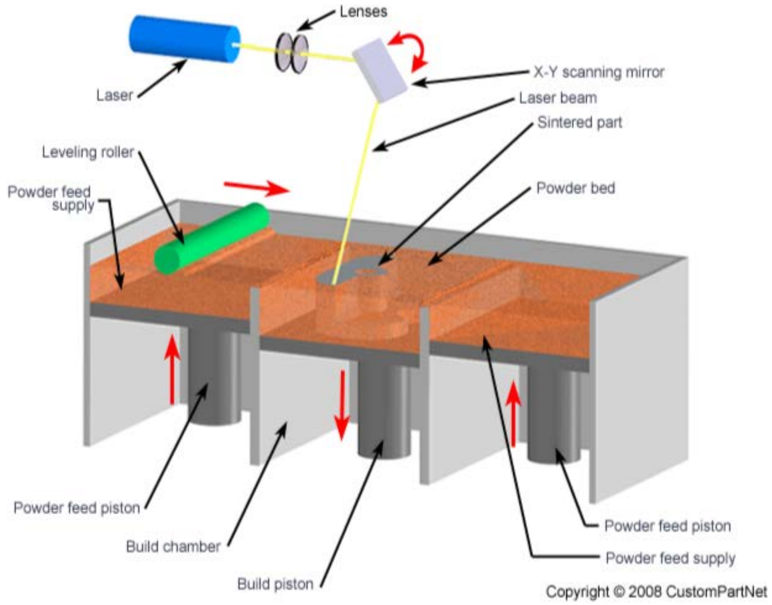


Figure 28 illustrates the working principle of PBF.

Fused Deposition Modeling (FDM): The material is extruded through a nozzle that follows a programmed path to print a thin layer (0.15-0.25 mm) onto a hot build plate (Ngo et al. 2018). After printing the first layer, the nozzle moves up to repeat the process for a new layer that is combined with previous layers to form the final part. This method produces parts that have good structural properties and multiple colors (Gibson, Rosen, and Stucker 2015). On the other hand, the large parts have poor surface finish and low resolution (Bhushan and Caspers 2017). FDM is an inexpensive and reliable, so it used in an office environment. The schematic of FDM (CustomPartNet 2018) that illustrates the working principle is shown in Figure 29.

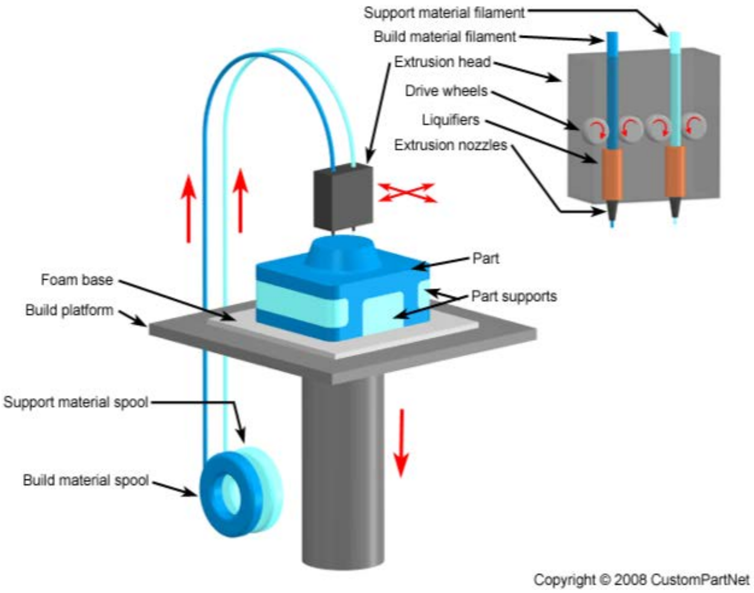


Figure 29 illustrates the working principle of FDM.

Binder Jetting (3D Printing): A liquid binding agent is applied onto thin layers of powder material bed to build up parts (Ngo et al. 2018). The powder bed moves down by layer thickness and a new layer of powder is spread on top the first printed layer as the binder liquid bonds the layers together (Gibson, Rosen, and Stucker 2015). The process repeats until the part is formed layer by layer. The binders include organic and inorganic materials. Parts are self-supporting in the powder bed so that support structures are not needed. .(Gibson, Rosen, and Stucker 2015). The finished part is left in the powder bed to make the binder set fully, and the green part to gain strength (Sandeep and Chhabra 2017). Metal or powdered ceramic parts are typically fired in a furnace after they are printed. 3D printing method produces parts of various materials such as plastic, metal, ceramics, and sand. The schematic of BJ-3DP (CustomPartNet 2018) that illustrates the working principle is shown in Figure 30.

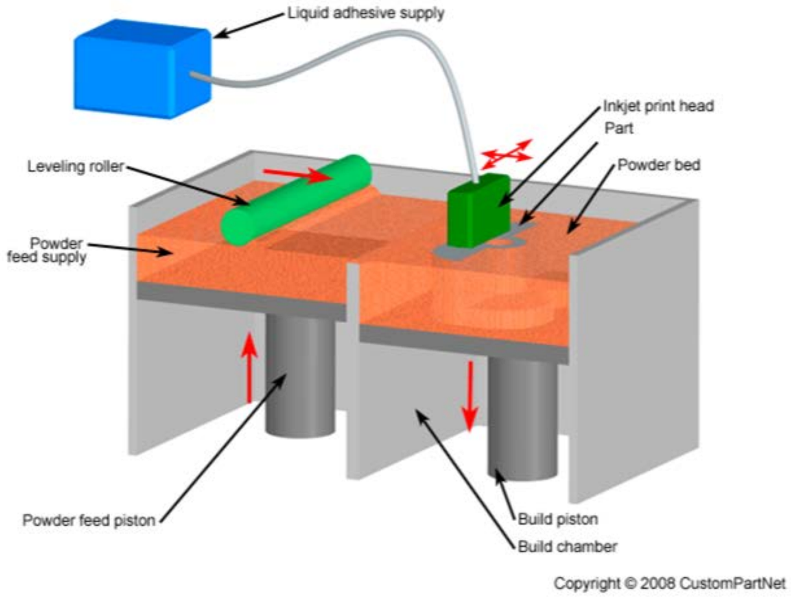


Figure 30 illustrates the working principle of BJ-3DP.

Directed Energy Deposition (DMD): A laser beam or a focused heat source is used to generate a melt pool on the base substrate (Gibson, Rosen, and Stucker 2015). The metal powder is fed through a nozzle into the melt pool, where it is melted. The melted material is deposited and solidified into the substrate (Ngo et al. 2018). Each pass of the BD head creates a track of solidified material, and adjacent lines of material make up layers (Gibson, Rosen, and Stucker 2015). A successive new layer is deposited and bonded to the underlying layers. This process repeats until a 3D object is built. DMD process is a form of automatic build-up welding, so it effective for repairing and adding features to existing components. This method can deposit multiple materials with high deposition rate on a single part at any direction or axis. The schematic of DMD (CustomPartNet 2018) that illustrates the working principle is shown in Figure 31.

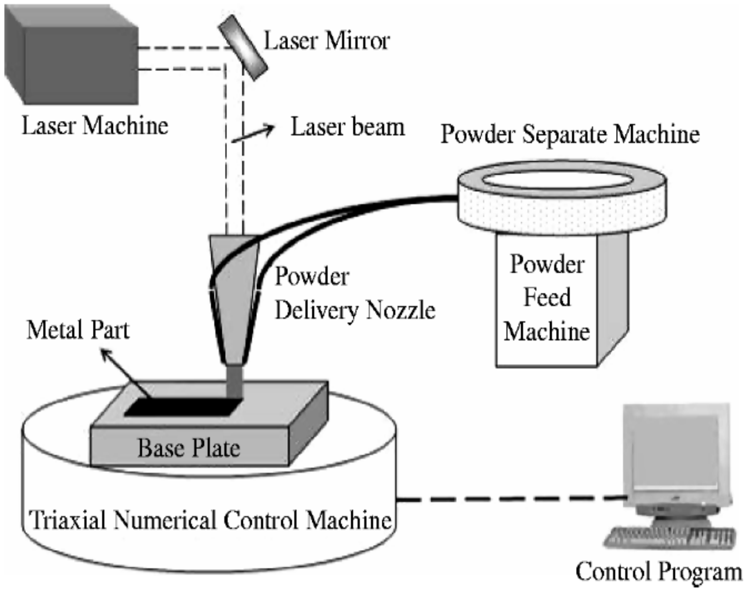


Figure 31 illustrates the working principle of DMD.

Laminated Object Manufacturing (LOM): The object is formed by stacking and laminating material sheets layer-by-layer. The LOM process uses an adhesives or chemical (paper/ plastics), ultrasonic welding, or brazing (metals) to bond layers together (Gibson, Rosen, and Stucker 2015). Laser beam cuts unneeded regions of each layer precisely by following the counter of the part's CAD model (Sandeep and Chhabra 2017). After the object is built, the excess portion of sheet is removed. This method has a high volumetric build rate, relatively low cost, and less manufacturing time. LOM process can be used to combine a variety of materials foils, including embedding components. The schematic of LOM (CustomPartNet 2018) that illustrates the working principle is shown in Figure 32.

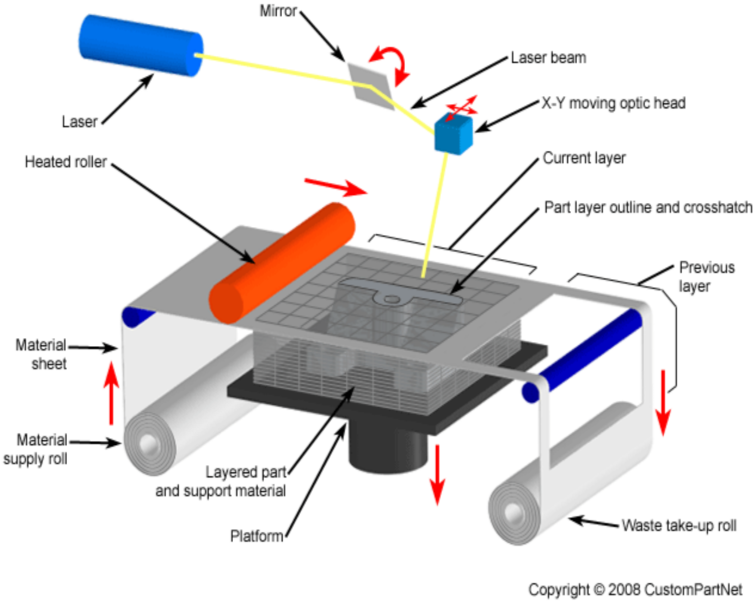


Figure 32 illustrates the working principle of LOM.

Material Jetting (MJ): A UV light is used to activate droplets of photocurable resin that is deposited layer by layer to make parts (Gibson, Rosen, and Stucker 2015). Hundreds of tiny nozzles are dispensing the photopolymer resin at predetermined areas to build a part layer-by-layer (Ngo et al. 2018). The droplets are deposited directly onto a base substrate, where that photocurable hardens and becomes the part itself rather than just as a binder (Gibson, Rosen, and Stucker 2015). Parts can be built from different materials such as photopolymers, wax, or metals that cure or harden when exposed to UV light or elevated temperatures. The MJ process requires post-processing to remove the dissolvable material support, and heat treatment to increase the bonding strength between layers (Sandeep and Chhabra 2017). This method has a high level of accuracy and a moderate surface quality. The contour crafting method uses the principle of material jetting to print large building structures. The schematic of MJ (CustomPartNet 2018) that illustrates the working principle is shown in Figure 33.

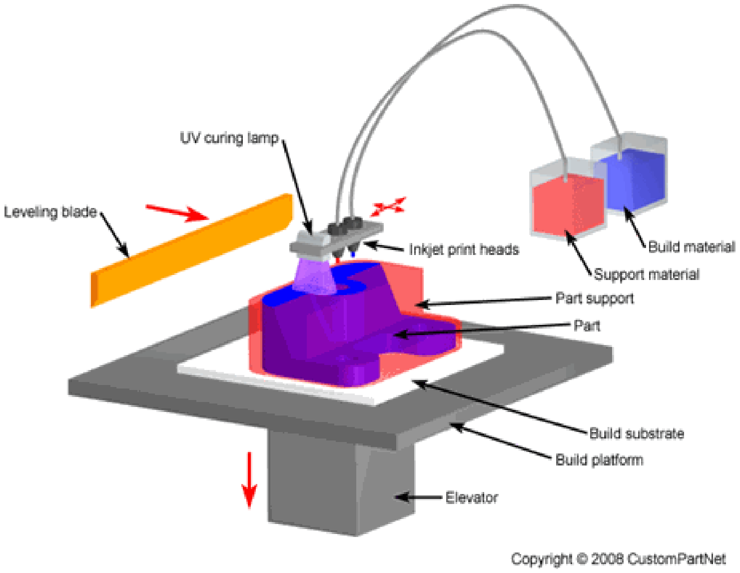


Figure 33 illustrates the working principle of MJ.

Hybrid Manufacturing Technologies: Additive manufacturing and subtractive machining can be performed together in a single machine. The strengths of both processes can be utilized to produce complex parts. For example, laser metal deposition is combined with CNC machining for coating and repairing cost intensive parts such as turbine blades (Merklein et al. 2016). In the aviation and space industry, it is preferable to repair defective high-value components or worn surfaces using the hybrid process than to replace them (Graf et al. 2013). This process generates slight distortion and produce smooth surface finish.

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