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THREE-DIMENSIONAL (3D) PRINTING: JOLTS ON SUPPLY CHAIN MANAGEMENT AND THE CHINESE MANUFACTURING INDUSTRY

In May and June 2013, a giant rubber duck designed by a famous conceptual artist Florentijn Hofman floated outside the Ocean Terminal of Tsim Sha Tsui Hong Kong, attracting more than eight million local and overseas tourists. Inside the Ocean Terminal, Toys"R"Us, the largest toy retailer in Hong Kong, held a "Bye-Bye Duck Party" at its Ocean Terminal flagship shop and sold mini-ducks 2.3 inches tall and 2 inches wide for US$62.[1] Unlike mini-ducks manufactured by traditional injection-mold technology[2] in Chinese factories and transported to retail shops in Hong Kong, the mini-ducks sold at Toys"R"Us's Ocean Terminal flagship shop were "fresh and hot" products. In collaboration with 3D Systems[3], a leading provider of three-dimensional ("3D") printing and manufacturing solutions, Toys''R''Us printed mini-ducks on-site at its flagship shop and sold them immediately to customers [See **Exhibit 1** for 3D-printer production of mini-ducks on-site]. Experiencing 3D-printing, retail consumers could see how final products were made and even join in the design process to get tailor-made items.

Conceived by American engineer Chuck Hull[4] and patented in the USA in the 1980s, 3D printing, officially named "additive manufacturing" in technical standards, was a bottom-up process by which materials were laid down in thin successive layers until an object was fully constructed. As an innovation in technique, 3D printing made production conducted at or near the points of purchase or consumption possible. This had a huge impact on traditional supply chain management and manufacturing industry. A variety of key 3D-printing patents expired in 2014, stimulating mass production and adoption of 3D-printing devices and the improvement of 3D-printing techniques. A Deloitte report predicted that 220,000 3D printers, worth US$1.6 billion, would be sold worldwide in 2015.[5] What was the impact of 3D printing on the manufacturing industry and supply chain management? Will China, the largest manufacturing

[1] 3ders (2013) "3D printed mini yellow ducks debut in Hong Kong", http://www.3ders.org/articles/20130606-3d-printed-mini-yellow-ducks-debut-in-hong-kong.html (accessed 30 January 2015)
[2] Injection molding was a traditional manufacturing process to produce parts through which materials such as mental, glass powder or plastic were melted and then injected into a mold.
[3] 3D Systems was founded in 1986 by Chuck Hull, the inventor of 3D printing.
[4] Chuck Hull was also known as W. Chuck Hull.
[5] Deloitte (2013) "Disruptive manufacturing: The effects of 3D printing", https://www2.deloitte.com/content/dam/Deloitte/ca/Documents/insights-and-issues/ca-en-insights-issues-disruptive-manufacturing.pdf (accessed 30 January 2015).

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nation, lose that status or can the country leverage the 3D-printing trend to reinforce the power of its manufacturing industries?

3D Printing: Conception, Technique and Patent

Conception

In 1983, Chuck Hull, the inventor of 3D printing, worked for a small company that used ultra-violet light techniques to make coatings for furniture such as tables.[6] Radiated by ultra-violet light, coating materials changed immediately from liquid to thin solid layers of plastic-like veneer.[7] Inspired by this production process, Hull wondered whether there was an innovative way to apply this technique. Could he design a bottom-up process that would lay down thousands of successive thin layers of materials on top of one another to construct three-dimensional objects of nearly any desired shape? Such an on-site process might efficiently and effectively transform digital computer designs into concrete objects. Hull began to conceive and test his ideas in a small lab during his spare time. One night in 1984, some months later, he invented stereolithography[8].

> *The class of materials is called "photopolymers" and these are typically acrylic-based materials that would be liquid until they're hit with -- let's say -- an ultra-violet light. Then, they instantly turn solid. So, you have a vat of this liquid and a point of ultraviolet light, and you turn it into a solid piece of plastic. That's the basic methodology. That is stereolithography. That's never changed.* [9]
>
> - Chuck Hull, inventor of 3D printing

Hull not only invented 3D printing but also made this invention into a business opportunity. In 1986, Hull patented his invention, stereolithography, obtaining U.S. Patent 4575330A. He soon founded a company, 3D Systems, to secure his invention's business opportunities. The new company got US$6 million funding from a Canadian investor and released its first commercial products in 1988.[10] Thirty years later, in 2015, 3D Systems was a leading provider of 3D printers, printing materials and printing solutions.

[6] Ponsford, M. and Glass, N. (14 February 2014)."The night I invented 3D printing", Cable News Network, http://edition.cnn.com/2014/02/13/tech/innovation/the-night-i-invented-3d-printing-chuck-hall/ (accessed 12 February 2015).

[7] Hickey, H. (22 June 2014) "Chuck Hull: the father of 3D printing who shaped technology", http://www.theguardian.com/business/2014/jun/22/chuck-hull-father-3d-printing-shaped-technology (accessed 12 February 2015

[8] Stereolithography, also known as optical fabrication, made layer-by-layer production of 3D objects possible. Computer-aided design (CAD) software sliced the design of a 3D object into thousands of thin horizontal 2-D layers. A computer-controlled beam of ultra-violet light shaped the object lay-by-layer by focusing its beam on the surface of acrylic-based materials, such as photopolymers. Radiated by ultra-violet light, the material changed instantly from liquid to solid, and a 2-D thin layer of the object was created. Another layer was then put on top of the previous layer. The process ended when the whole object had been shaped.

[9] Ponsford, M. and Glass, N. (14 February 2014). "The night I invented 3D printing", Cable News Network, http://edition.cnn.com/2014/02/13/tech/innovation/the-night-i-invented-3d-printing-chuck-hall/ (accessed 12 February 2015).

[10] Hickey, H. (22 June 2014) "Chuck Hull: the father of 3D printing who shaped technology", http://www.theguardian.com/business/2014/jun/22/chuck-hull-father-3d-printing-shaped-technology (accessed 12 February 2015).

Technique

Nowadays, 3D printing, officially called "additive manufacturing" in technical standards, was able to shape concrete objects from various substances ranging from traditional materials, such as plastic, paper, glass, ceramics, wax and metal, to living biological cells.[11] Besides the stereolithography Hull invented, various other 3D-printing techniques were available today, each with its special characteristics and applications [See **Exhibit 2** for key 3D-printing techniques]. All these techniques, similarly to the process Hull invented, constructed objects layer-by-layer through a bottom-up process. Once a thin layer is formed, another thin layer was then shaped on the top of previous layer until the whole object was fully constructed. Some techniques used beams of laser or ultra-violet light to shape thin layers, while others used heat to melt substances and then deposited these melted materials or powders on the top of the previous layer.

Patent

In mid-1980s when Chuck Hull originally conceived the 3D printing technique, he predicted that the technique would take 25 to 30 years to find applications for non-industrial customers and reach homes.[12] His prediction was accurate: the widespread commercialization and adoption of 3D solutions has not happened until in recent years. However, 30 years is a long time, and other factors might have hindered mainstream applications of the 3D printing technique. The conventional view held that intellectual property protection, such as patents, could provoke innovation by generating competition. However, some innovators suggested that patents block innovation. Because companies were concerned about potential intellectual-property infringement lawsuits, they were unlikely to invest funds and resources in 3D-printing research and development, holding back further development of and innovation in 3D-printing techniques.[13]

U.S. patents generally expired after twenty years. Although US patent 4575330A (Stereolithography (SLA), invented by Hull) expired in 2004, many other patents of key 3D-printing techniques remained for years, protecting the technology and blocking competitors. In addition, 3D-printing companies never stopped filing new patents for improvements in 3D-printing techniques. The number of 3D-printing patents granted began to accelerate in 2006 and has erupted since 2012, forecasting more innovation and improvement of 3D-printing techniques in the coming years [See **Exhibit 3** for trends in 3D-printing patent publication].

It was expected that 2014 would be a milestone for 3D-printing techniques, as a number of patents on 3D-printing techniques essential to the manufacture of the most advanced 3D printers expired that year, thereby stimulating an explosion in innovative techniques that would make lower-cost 3D-printing solutions possible [See **Exhibit 4** for key 3D-printing technique patents]. Something similar happened in 2009 on the expiration of a key 3D-printing patent covering fused deposition modelling (FDM), invented by Scott Crump.[14] During the period when the FDM patent was enforced, FDM 3D printers cost more than US$10,000. A few years after the patent expiration, the price of FDM 3D printers slumped and lots of different FDM open-source printers and software appeared, sparking a FDM 3D-printing boom. Scott Crump, FDM's

[11] Manyika, J. et al. (May 2013) "Disruptive technologies: Advances that will transform life, business, and the global economy", McKinsey & Company
[12] Hickey, H. (22 June 2014) "Chuck Hull: the father of 3D printing who shaped technology", http://www.theguardian.com/business/2014/jun/22/chuck-hull-father-3d-printing-shaped-technology (accessed 12 February 2015).
[13] Hornick, J. and Roland, D. (29 December 2013) "Many 3D Printing Patents Are Expiring Soon: Here's A Round Up & Overview of Them", http://3dprintingindustry.com/2013/12/29/many-3d-printing-patents-expiring-soon-heres-round-overview (accessed 12 February 2015).
[14] Quartz (21 July 2013) "3D printing will explode in 2014, thanks to the expiration of key patents", http://qz.com/106483/3d-printing-will-explode-in-2014-thanks-to-the-expiration-of-key-patents (accessed 12 February 2015).

inventor, predicted that within a few years after the 2014 expiration of patents on key 3D-printing techniques, especially on the apparatus that produced high-resolution 3D objects by selective sintering (SLS), competition would become fiercer and prices of SLS 3D printers would drop.[15]

> *This is what happened with FDM. As soon as the patents expired, everything exploded and went open-source, and now there are hundreds of FDM machines on the market. An FDM machine was $14,000 five years ago and now it's $300.*[16]
>
> - Scott Crump, FDM inventor of FDM and Statasys founder

Ironically, during the FDM-printer boom following 2009, most low-cost FDM 3D printers were made not in the US, where the technique originally arose, but in China, a country with a special innovation style, that of "imitative innovation."[17]

3D-printing Innovation in China

Rather than conducting independent research or empirical experiments, Chinese technology companies preferred imitation. These technology companies did not directly "copy-and-paste" existing techniques, designs or ideas, but extracted essential factors they found interesting and adapted them as critical components of their new techniques, designs and ideas. Once a product with advanced techniques or distinct design became popular, Chinese companies quickly imitated those techniques and designs, making adaptations and improvements and producing similar but new products with Chinese brands. Imitation sparked a particularly Chinese style of innovation - imitative innovation. This made Chinese production with advanced technologies and popular designs much lower in cost. By making some improvements, Chinese companies could create new products with more functionality, better design and even technical advantages when compared with the products imitated.

Recent Chinese imitative innovation of 3D-printing techniques received government support. In late 2012, realizing that China lagged far behind the US in advanced 3D-printing manufacturing techniques, the Chinese Ministry of Industry and Information Technology established the "China 3D-Printing Technology Industry Alliance." It invested around US$3.3million to set up ten 3D-printing research and innovation centers in China, which were to employ advanced 3D printing technologies, support manufacturers and accelerate innovation, improvement and differentiation of China's own 3D-printing techniques.[18] In January 2015, Winsun, a Chinese high-tech company, using construction waste and its advanced giant 3D printer, built the world's first and tallest 3D-printed residence, a 1,100 square meter five-story apartment building that met national building standards.[19]

[15] Ibid.

[16] Ibid.

[17] Imitative innovation (or shanzhai innovation 山寨创新 in Chinese) means imitative adoption or adaptation of another independent innovation.

[18] Mu, G. (14 May 2013) "Manufacturing group to build 3D printing innovation centers", http://en.people.cn/90778/8242953.html (accessed 12 February 2015).

[19] 3ders (18 January 2015) "WinSun China builds world's first 3D printed villa and tallest 3D printed apartment building" http://www.3ders.org/articles/20150118-winsun-builds-world-first-3d-printed-villa-and-tallest-3d-printed-building-in-china.html (accessed 12 February 2015).

China can consider developing an industry-led strategic transformation plan to focus on technological innovation and differentiation. It can enact policies that bring in capital and technology--intensive industries from developed countries and it should work on improving how to utilize innovations imported from other co incline countries.[20]

- Ricky Tung, Deloitte China partner

3D Printing: Adoption, Advantages and Limitations

At the early stage, 3D printing was mainly used for rapid prototyping. It then expanded into rapid manufacturing. Today, 3D printing was widely used in the manufacturing, automotive, and aerospace industries, architecture, medicine, education and new business. Materials used in 3D printing included almost every key substance used in both consumer and industrial manufacture, such as plastic, polyester, glass, ceramic, powder, metal and even food and living cells. Many supporters of 3D printing proposed that this technology would bring another industrial revolution, although other observers doubted the widespread application of this technology, saying that the limitations of the technology itself would hinder high adoption levels.[21] This dispute could not be solved by reaching a conclusion inclined to either side because of the subject's complexity. McKinsey proposed a compromise view that 3D printing definitely had potentially disruptive effects on product design, production, distribution and sales, but it would take years before the impact was felt in a wide range of goods and industries.[22] Similarly, Deloitte predicted that 220,000 3D printers, worth US$1.6 billion, would be sold worldwide in 2015, but that it was unlikely that 3D printers would reach every home and turn each home into a factory. In other words, the impact of the 3D-printing revolution would be felt in industrial markets rather than among individual consumers.[23]

Adoptions

Although 3D printing was not sophisticated enough to make an advanced automobile or iPhone, the technology was widely adopted to make particular automobile parts and tailor-made accessories, such as covers and protection cases and for iPhones.[24] A survey conducted by PwC showed that in 2014, 66.7% of manufacturers were adopting 3D printing techniques in prototyping or production, while 24% planned to do so in the future. Only 8.6% of manufacturers were not interested in adopting this technique.[25] 3D printers were widely used to print design prototypes, automotive parts, fashion items, medical implants and even living tissues.

Prototyping

Rapid prototyping was the earliest application of 3D-printing techniques in the manufacturing and automotive industries. Traditional prototyping was a time- and cost-intensive process that used molds or dies. New product designs were sent from North American or European design

[20] Mu, G. (14 May 2013) "Manufacturing group to build 3D printing innovation centers", http://en.people.cn/90778/8242953.html (accessed 12 February 2015).
[21] Manyika, J. et al. (May 2013) "Disruptive technologies: Advances that will transform life, business, and the global economy", McKinsey & Company
[22] Ibid.
[23] Deloitte (2013) "Disruptive manufacturing: The effects of 3D printing", https://www2.deloitte.com/content/dam/Deloitte/ca/Documents/insights-and-issues/ca-en-insights-issues-disruptive-manufacturing.pdf (accessed 30 January 2015).
[24] The Economist (21 Apr 2012) "A third industrial revolution", http://www.economist.com/node/21552901 (accessed 12 February 2015).
[25] PwC (June 2014) "3D printing and the new shape of industrial manufacturing", http://www.pwc.com/us/en/industrial-products/3d-printing.jhtml (accessed 12 February 2015).

centers to factories, mostly in China. The factories prepared molds or casts based on design requirements and then made the prototype. The prototype was shipped back to the design centers located 6,000 to 8,000 miles away. The whole prototyping process generally took two to three months. If designers were not satisfied with the prototype, the cycle was repeated. In contrast, with 3D printers, designers could not only print their designs on-site and see the printed object immediately, but also make necessary changes or improvements on the same day. This shortened the product-development period and accelerated the frequency of new-product releases considerably. At the North American International Auto Show in 2014, Ford announced that it had adopted 3D printing and was skipping the traditional step of sand-mold design. It had printed a prototype engine cover for a new-model car, which was the 500,000th part so printed.[26]

Industrial parts

One of the most widespread industrial 3D-printing adoptions occurred in the automotive industry. 3D printers could not only print parts for cars in automotive manufacturing plants, but made replacement parts at or near locations where car were being repaired, enhancing production efficiency and reducing the replacement-part delivery waiting times. At the North American International Auto Show in January 2015, Local Motors, a vehicle innovation start-up, manufactured a car on-site in the show room. Using carbon polymers, a 3D printer printed the car's frame and interior, and afterwards workers installed a motor and tires on the printed car, making the car ready for the road.[27] At the auto show John Rogers, Founder and CEO of Local Motors, stated that the printed car was not merely an experiment but a development that allowed people to print tailor-made cars anytime in any community where a 3D printer was available.

As was the case with the automotive industry, the airplane industry also adopted 3D printing of parts. In April 2012, the first 3D printer was installed at Airbus's plant and soon printed its first airplane part. Fifteen months later, nearly 1,3000 airplane parts were printed by 3D printers in the Airbus plant, reducing lead-time on supply tooling and costs by 70%.[28] In 2014, a 3D-printed plastic component was used on a commercial Airbus A310 aircraft for the first time, forecasting a revolution in the global airline-industry spare-parts supply business. Thanks to this technique, a North America-based airline company could print spare parts on-demand in Asia, where the printed spare parts were required. Traditionally, these parts were transported from the airline's North American to Asia or stored in every destination the airline served, incurring high transportation costs, long waiting times and high inventory costs. A 2014 PwC report showed that 3D printing would benefit the global airline industry by lowering airline inventory costs and realize as much as US$1.8 billion in additional pre-tax profits annually.[29]

Low-volume and tailor-made products

Another widespread adoption of 3D printing was in the production of low-volume and tailor-made products, an adoption that expanded 3D-printing applications from prototyping to final-product manufacturing. Traditional manufacturing processes used mass-production techniques to reduce unit costs. Like traditional prototyping, mass-production processes required many manufacturing steps, such as mold design, material injection, cutting and assembling. These steps were time-consuming and costly and were inefficient in the production of low-volume or tailor-made products. Moreover, traditional manufacturing utilized a "parts and assembly"

[26] Ibid.

[27] Kessler, A. (15 January 2015) "A 3-D Printed Car, Ready for the Road", The New York Times, http://www.nytimes.com/2015/01/16/business/a-3-d-printed-car-ready-for-the-road.html?_r=0 (accessed 12 February 2015).

[28] The AirbusVoice Team (15 July 2014) "How 3D Printing Is Delivering Airplane Parts On Demand", Forbes,http://www.forbes.com/sites/airbus/2014/07/15/how-adding-a-new-dimension-to-airplanes-is-delivering-parts-on-demand (accessed 12 February 2015).

[29] PwC (June 2014) "3D printing and the new shape of industrial manufacturing", http://www.pwc.com/us/en/industrial-products/3d-printing.jhtml (accessed 12 February 2015).

process that limited final-product complexity. In contrast, 3D printing could print complex items all at once, simplifying production and producing complex items impossible to make through traditional manufacturing. Consumer preferences and behaviors have recently changed considerably and the demand for personalized products had surged. 3D printing provided an unprecedented advanced solution for companies wanting to respond to this trend, making low-volume production possible and saving design and assembly time and costs. In addition, because the production process has moved from factories to locations at or near points of purchase or consumption, consumers could join in the design process and get tailor-made items immediately. McKinsey predicted that the market for low-volume, highly personalized and complex products such as medical and dental implants, fashion items, clothing accessories and engine parts would reach US$770 billion in 2025. 30% to 50% of these products might be made by 3D printing techniques, cutting production costs by 40% to 55% by reducing materials waste, assembly time and labor costs.[30] A recent PwC innovations survey showed that 50% of manufacturers were likely or very likely to adopt 3D printing in producing low-volume, highly personalized items in the coming three to five years. 20% were convinced that 3D printing would be used for mass production in the future.[31]

Advantages

Unlike traditional manufacturing processes that require a full cycle of design, mold preparation, parts production, cutting, assembling, long-distance transportation, warehouse storage and sale, 3D printing allowed decentralized manufacturing at or near the point of purchase or consumption. Thanks to 3D-printer reduction of production and delivery time, an inspiration or idea could be transformed from a digital design file to a concrete object immediately at or near designer's location. An innovative idea could be manufactured and reach its potential customers quickly. Manufacturing wastes could be greatly reduced. Complex objects with special internal structures impossible to produce through traditional manufacturing processes could be printed immediately.[32] Daniel Toon, innovation consultant at PA consulting, predicted that 3D printing would make localized manufacturing possible and alter current global import-and-export dynamics. He also predicted that communities could make whatever they need after installation of appropriate 3D printers.[33] Aside from flexibility, 3D printing would also bring lower costs and boost innovation in manufacturing.[34] McKinsey predicted that the widespread potential applications of 3D printing in the coming years would benefit companies and dramatically increase the market penetration rate of 3D printing, which had less than a 10% market share in 2014 [See **Exhibit 5** for possible applications of 3D printing and its benefits].[35]

Limitations and Concerns

Limitations of a technology can hinder its widespread adoption and application, and 3D printing is no exception. Limitations of 3D printing included maintenance, slow printing speeds, high costs, limitations on product size, materials availability, quality, utility and lack of scalability. A 2014 PwC survey in 2014 listed the main obstacles in 3D-printing adoption and showed that printing quality and shortage of technical expertise were critical obstacles [See **Exhibit 6** for

[30] Manyika, J. et al. (May 2013) "Disruptive technologies: Advances that will transform life, business, and the global economy", McKinsey & Company

[31] PwC (June 2014) "3D printing and the new shape of industrial manufacturing", http://www.pwc.com/us/en/industrial-products/3d-printing.jhtml (accessed 12 February 2015).

[32] Manyika, J. et al. (May 2013) "Disruptive technologies: Advances that will transform life, business, and the global economy", McKinsey & Company

[33] Bird, J. (8 August 2012) "Exploring the 3D printing opportunity", *The Financial Times*

[34] Cohen, D. et al (February 2015) "Are you ready for 3-D printing?", McKinsey Quarterly, http://www.mckinsey.com/insights/manufacturing/are_you_ready_for_3-d_printing?cid=other-eml-alt-mkq-mck-oth-1502 (accessed 24 February 2015)

[35] Ibid.

obstacles to 3D-printing adoption].[36] McKinsey found that material costs for 3D printing in 2013 were nearly 50 to 100 times higher than those for traditional injection molding. It also predicted that as demand increased in coming years, costs would rapidly decline.[37] In China, one plastic manufacturer started to produce and sell plastic filaments at attractive prices around five times higher than those of traditional plastic manufacturing.[38]

Concerns about the adoption of 3D printing techniques, such as intellectual property protection issues and ethics, also arose. With a digital design file and a 3D printer, anyone could print a product, but the digital design file itself could be protected by copyright. In February 2015, Australian police arrested a 28-year-old man who possessed gun parts, printed by a 3D printer, which could have become complete weapons after simple assembly.[39]

Typical Supply Chain Networks

In a typical supply chain network, raw materials were supplied, parts produced and final products assembled in one or more locations. The final products were then transported to warehouses or distribution centres for intermediate storage at or near the points of final consumption. Finally, the products reached retail stores and customers [See **Exhibit 7** for a typical supply chain network].[40] Aside from materials and manufacturing costs, which were relatively fixed, transportation and inventory costs were flexible and could affect the efficiency and effectiveness of the whole supply chain. The essential challenges for supply chain design and operations could not be determined by any isolated part of the network, but focused on how to minimize total system-wide costs while maintaining system-wide service levels.[41] In this typical supply chain network, materials and factory, warehouse, retail and customer locations were dispersed. Products made in factories where materials were abundant and labor and manufacturing costs low might travel 8,000 miles, say from China to consumers in the east coast of the US. In addition, customer requirements and preferences changed quickly, increasing supply chain management uncertainty and difficulties. Manufacturers always produced too many less-popular products and too few best-selling products due to the difficulty of predicting demand. For example, a shoe company might be able to predict the aggregate amount of shoes to be sold in the coming season, while still finding it difficult to get a clear picture of how many shoes of certain colors and sizes should be made.

3D printing was likely to provide a solution to these supply chain management challenges by printing low-volume and tailor-made products on-site, a solution that would also reduce materials-supply risks, supply chain network complexity and inventory costs by manufacturing final products at or near points of purchase or consumption by a decentralized production process [See **Exhibit 8** for a comparison of traditional and 3D-printing supply chains]. In considering the potential impact of widespread adoption of 3D printing on typical supply chain networks and the manufacturing industry, some observers optimistically predicted that manufacturing would go digital, bringing about another industrial revolution.[42]

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[36] PwC (June 2014) "3D printing and the new shape of industrial manufacturing", http://www.pwc.com/us/en/industrial-products/3d-printing.jhtml (accessed 12 February 2015).
[37] Manyika, J. et al. (May 2013) "Disruptive technologies: Advances that will transform life, business, and the global economy", McKinsey & Company
[38] Ibid.
[39] BBC (11 February 2015) "3D-printed knuckle dusters and gun parts seized in Australia", http://www.bbc.com/news/technology-31416838 (accessed 12 February 2015).
[40] David Simchi-Levi (2007) *Designing & Managing the Supply Chain*, 3rd edition, McGraw-Hill, pp. 1-2.
[41] Ibid.
[42] The Economist (21 Apr 2012) "A third industrial revolution", http://www.economist.com/node/21552901 (accessed 12 February 2015).

China's Manufacturing Sector

Manufacturing in China

China initiated economic reform in 1978, transiting from a planned to a market economy, gradually weakening government control over enterprises and attracting foreign investment. Thirty years after the economic reform, China was a global manufacturing powerhouse. In 2011, China replaced the US as the top producer of manufactured goods in the world. It leveraged this tremendous manufacturing power, enhancing living standards and doubling per-capita GDP in the period from 2003 to 2013.[43]

During the past two decades, taking advantage of low salaries, the ability to supply materials, huge infrastructural investment, and technical innovations, China, now known as the "world factory," became an extremely successful manufacturing exporter. At the same time, its domestic market was also enormous.[44]

Products were designed in Europe or the US, with design layouts and manufacturing requirements sent to China. China manufactured the products and then shipped them to retailers and customers around the world, increasing China's manufacturing and supply chain power. For example, iPhones and iPads were designed by Apple in California and assembled in China. Assembled iPhones and iPads were then transported to Apple retail stores around the world by typical supply chain networks or to end users by direct courier.

At the same time, middlemen responsible for coordinating manufacturing requirements and processes emerged in China. Li & Fung, a Hong Kong-based company, was successful in finding Chinese manufacturers to make goods for global customers such as Wal-Mart and Target. Li & Fung cost-competitively supplied everything from shoes, clothes and bags to toys and even decorative packing boxes, all made in China.

However, in recent years, appreciation of the Renminbi, China's official currency, raising labor costs, disruptive technologies, and changes in consumer preferences and behavior threatened China's competitive advantages in manufacturing and the country's export sector.[45]

The HSBC China Market Purchasing Managers' Index (PMI) for January 2015 showed a tumble to a level of 49.7, just lower than the critical 50 level that separates growth from contraction [See **Exhibit 9** for HSBC China Manufacturing PMI 2004-2014].[46] In addition, employment in factories continued to shrink, with January 2015 representing the 15th month of this shrinking trend.[47]

3D-Printing Manufacturing in China

Imitative innovation, well-established manufacturing infrastructure and relatively low labor and material costs made rapid growth of 3D-printer manufacturing in China possible. Lux Research predicted that sales of 3D printers manufactured in China would reach 37,900,valued at US$109 million, in 2018, four times the 2014 numbers and three times the market value.[48]

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[43] Eloot, K. et al (June 2013) "A new era for manufacturing in China", McKinsey Quarterly
[44] Ibid.
[45] Ibid.
[46] Reuters (1 February 2015) "China January HSBC factory PMI contracts for second month", http://www.reuters.com/article/2015/02/02/us-china-economy-pmi-idUSKBN0L603E20150202 (accessed 12 February 2015).
[47] Ibid.
[48] Jacques, C. (30 September 2014) "3D Printed in China – China Bids for Leadership in Emerging 3D Printing Technology", Lux Research Inc., http://www.luxresearchinc.com/news-and-events/press-releases/read/3d-printed-china-%E2%80%93-china-bids-leadership-emerging-3d-printing (accessed 12 February 2015).

Chinese companies were not satisfied with selling their imitative innovations to the limited domestic market, and were keen to expand their global business by leveraging their manufacturing and cost-competitive advantages. On February 11, 2015, Zhuhai CTC Electronic, a leading Chinese 3D-printer manufacturer established a London office and formally expanded into the European and UK markets, setting the stage for its overseas expansion and future development.[49] In 2013, taking advantage of lower production costs than those of leading global giants such as 3D Systems and MakerBot, Chinese 3D printer manufactures exported around 60% of their products, with 21,550 3D-printers manufactured and 12,810 exported.[50] Besides producing printers themselves, Chinese manufacturers also made efforts at establishing a 3D-printing ecosystem in China by producing 3D scanners and printing materials, as well as providing 3D-printing services and solutions [See **Exhibit 10** for China's Growing 3D-Printing Ecosystem].

Some observers suggested that, by making production at or near points of purchase or consumption possible, 3D printing would undermine China's current manufacturing and export status.

> *As manufacturing goes digital, it will change out of all recognition. And some of the business of making things will return to rich countries.*[51]
>
> - Paul Markillie, innovation editor of the Economist

However, in recent years, China has rapidly embraced the 3D-printing trend and explored the new, greatly expanded 3D-printing manufacturing and export market space, making this prediction somewhat premature.

Looking Forward

Wohlers Associates reports indicated that 3D printing demonstrated an annual growth rate of 34.9% in 2014 and expected it would quadruple in size in the coming four years.[52] In 2015, McKinsey predicted that in 2015 3D printing would begin to fulfil its promise, with much more widespread application in the coming five to ten years.[53]

What role could 3D printing play in changing supply-chain management? What are the advantages, disadvantages and limitations of 3D-printing technology compared with those of traditional manufacturing technology?

What could the short-term and long-term impact of 3D printing on the Chinese manufacturing industry be? Could China leverage the coming 3D-printing trend to reinforce the power of its manufacturing industry?

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[49] CNBC (11 February 2015) "Chinese 3D Printer Manufacturer Zhuhai CTC Electronic Opens London Office", (accessed 12 February 2015).

[50] Jacques, C. (30 September 2014) "3D Printed in China – China Bids for Leadership in Emerging 3D Printing Technology", Lux Research Inc., http://www.luxresearchinc.com/news-and-events/press-releases/read/3d-printed-china-%E2%80%93-china-bids-leadership-emerging-3d-printing (accessed 12 February 2015).

[51] *The Economist* (21 Apr 2012) "A third industrial revolution", http://www.economist.com/node/21552901 (accessed 12 February 2015).

[52] Wohlers Associates (2014) "Media Releases", http://www.wohlersassociates.com/press-releases.html (accessed 24 February 2015)

[53] Cohen, D. et al (February 2015) "Are you ready for 3-D printing?", McKinsey Quarterly, http://www.mckinsey.com/insights/manufacturing/are_you_ready_for_3-d_printing?cid=other-eml-alt-mkq-mck-oth-1502 (accessed 24 February 2015)

EXHIBIT 1: 3D-PRINTER PRODUCTION OF MINI-DUCKS ON-SITE

Source: 3ders (2013) "3D printed mini yellow ducks debut in Hong Kong", http://www.3ders.org/articles/20130606-3d-printed-mini-yellow-ducks-debut-in-hong-kong.html (accessed 30 January 2015)

EXHIBIT 2: KEY 3D-PRINTING TECHNIQUES

Stereolithography (SLA): A laser or other UV light source is aimed onto the surface of a pool of photopolymer (light-sensitive resin). The laser draws a single layer on the liquid surface; the build platform then moves down, and more fluid is released to draw the next layer. SLA is widely used for rapid prototyping and for creating intricate shapes with high quality finishes, such as jewellery.

Selective laser sintering (SLS): In this technique, a layer of powder is deposited on the build platform, and then a laser "draws" a single layer of the object into the powder, fusing the powder together in the right shape. The build platform then moves down and more powder is deposited to draw the next layer. SLS does not require any supporting structure, which makes it capable of producing very complex parts. SLS has been used mostly to create prototypes but recently has become practical for limited-run manufacturing. General Electric, for example, recently bought an SLS engineering company to build parts for its new short-haul commercial jet engine.

Direct metal laser sintering (DMLS): DMLS is similar to selective laser sintering but deposits completely melted metal powder free of binder or fluxing agent, thus building a part with all of the desirable properties of the original metal material. DMLS is used for rapid tooling development, medical implants, and aerospace parts for high-heat applications.

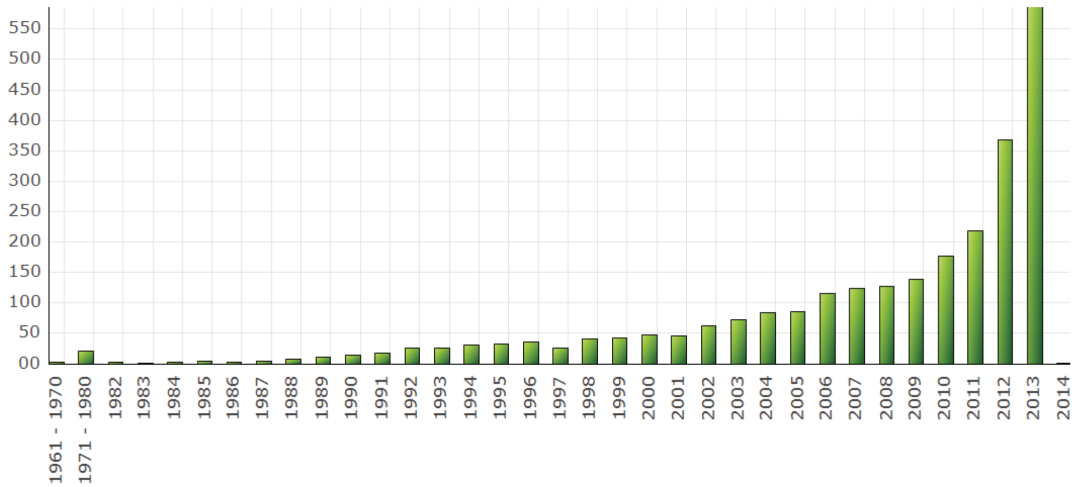
Fused deposition modelling (FDM): A filament of plastic resin, wax, or another material is extruded through a heated nozzle in a process in which each layer of the part is traced on top of the previous layer. If a supporting structure is required, the system uses a second nozzle to build that structure from a material that is later discarded (such as polyvinyl alcohol). FDM is mainly used for single- and multipart prototyping and low-volume manufacturing of parts, including structural components.

Laminated Object Manufacturing (LOM): A sheet of material (paper, plastic, or metal) is fed over the build platform, adhered to the layer below by a heated roller, and a laser cuts the outline of the part in the current layer. LOM is typically used for form/fit testing, rapid tooling patterns, and producing less detailed parts, potentially in full color.

Inkjet-bio-printing: Bio-printing uses a technique similar to that of inkjet printers, in which a precisely positioned nozzle deposits one tiny dot of ink at a time to form shapes. In the case of bio-printing, the material used is human cells rather than ink. The object is built by spraying a combination of scaffolding material (such as sugar-based hydrogel) and living cells grown from a patient's own tissues. After printing, the tissue is placed in a chamber with the right temperature and oxygen conditions to facilitate cell growth. When the cells have combined, the scaffolding material is removed and the tissue is ready to be transplanted.

Source: Manyika, J. et al. (May 2013) "Disruptive technologies: Advances that will transform life, business, and the global economy", McKinsey & Company

EXHIBIT 3: TRENDS IN 3D-PRINTING PATENT PUBLICATION



Source: Patent iNSIGHT Pro™ (2014) "3D Printing: Technology Insight Report", Gridlogics Technologies Pvt. Ltd.

EXHIBIT 4: KEY 3D-PRINTING TECHNIQUE PATENTS

Technique	Patent Publication Number	Original Assignee	Filing Year	Expiration Year
Apparatus for production of three-dimensional objects by stereolithography (SLA)	US 4575330	Uvp, Inc.	1984	2004
Apparatus and method for creating three-dimensional objects (FDM)	US 5121329	Stratasys, Inc.	1989	2009
Thermal stereolithography	US5569349	3D Systems, Inc.	1995	2013
Apparatus for producing parts by selective sintering (SLS)	US5597589	The University Of Texas System	1994	2014
Process of support removal for fused deposition modelling (FDM)	US5503785	Stratasys, Inc.	1994	2014
Apparatus and method for making three-dimensional articles using bursts of droplets	US5555176	Bpm Technology, Inc.	1994	2014
Increasing the useful range of cationic photoinitiators in stereolithography (SLA)	US5494618	Alliedsignal Inc.	1994	2014
Apparatus and method for thermal normalization in three-dimensional article manufacturing	US5572431	Bpm Technology, Inc.	1994	2014
Additive fabrication apparatus and method	US5529471	University Of Southern California	1995	2015
Selective laser sintering with composite plastic material	US5733497	Dtm Corporation	1995	2015
Lamination by solidifying a radiation exposed photopolymer	US5762856	Chuck Hull	1995	2015
Laminated object manufacturing system (LOM)	US5730817	Helisys, Inc.	1996	2016

Source: http://www.google.com/patents (accessed 30 January 2015)

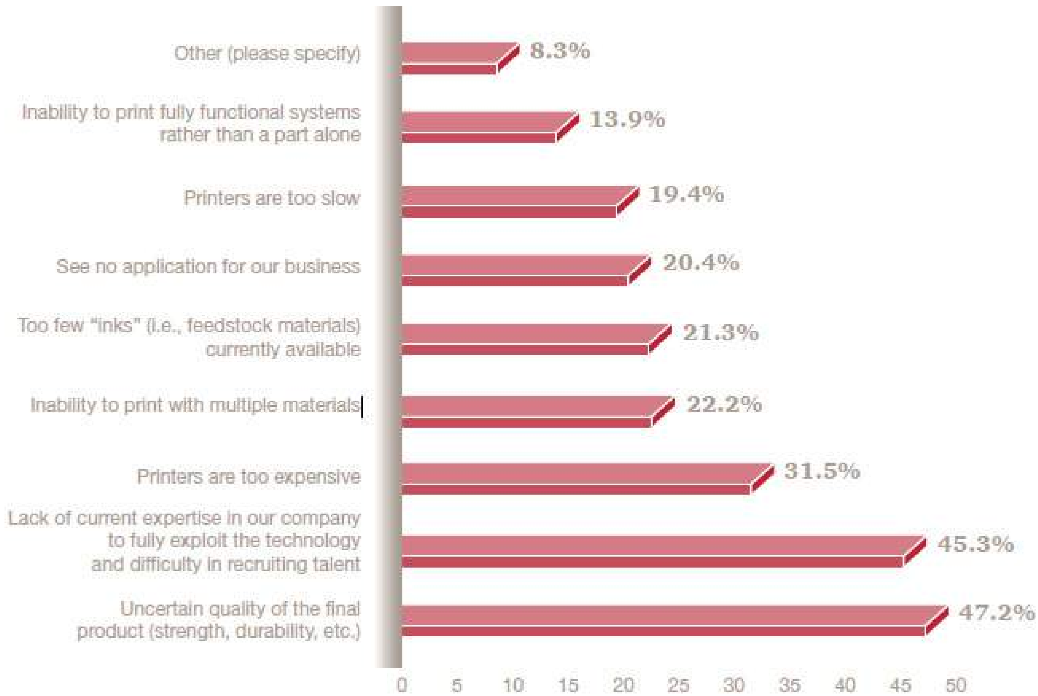
EXHIBIT 5: POSSIBLE APPLICATIONS OF 3D PRINTING AND ITS BENEFITS

New products and delivery models	New designs, enabled by cheap geometric complexity, that reduce weight and offer geometry-driven performance (eg, fluid dynamics) New delivery models (eg, mass customization)
Tooling	Savings on custom tooling that would otherwise amortize poorly over low production quantities Conformal tooling[1] enabled by the geometric complexity that 3-D printing affords
Assembly	Reduced assembly steps via printing integrated assemblies, cutting labor expenses and improving quality control
Inventory	Reduced inventory (legacy or spare parts) thanks to printing on demand
Improved product life cycle	Faster time to market Leaner, more iterative approach to design, reducing impact of both design-based and commercial uncertainty

[1]Molds with geometrically complex cooling channels that shorten injection-molding cycle times.

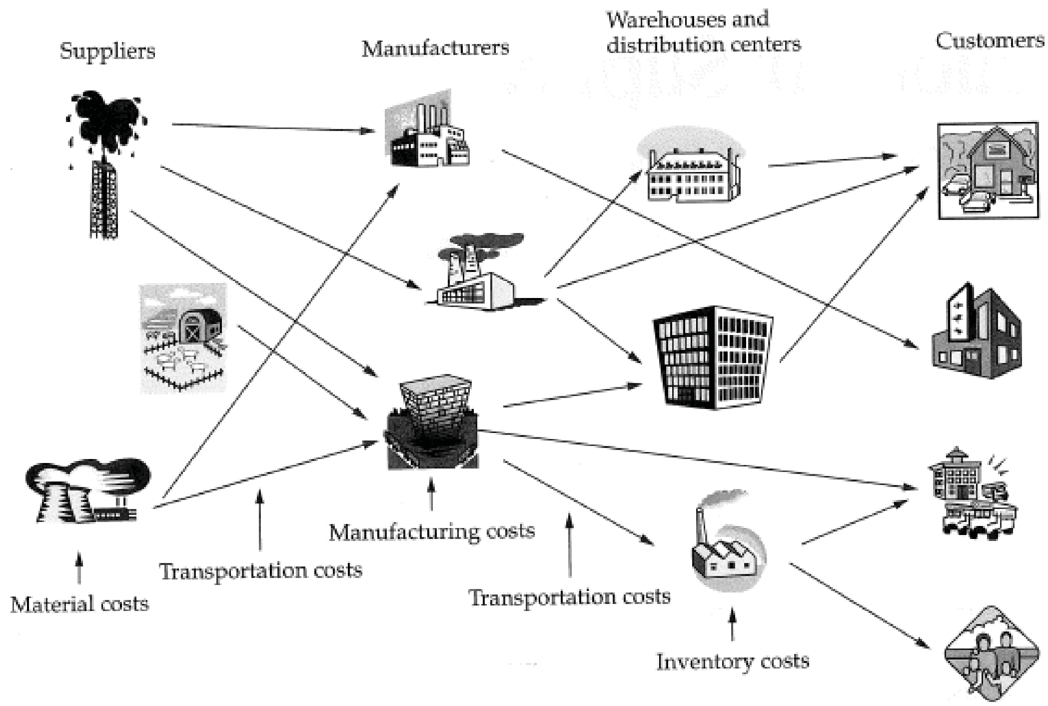
Source: Cohen, D. et al (February 2015) "Are you ready for 3-D printing?", McKinsey Quarterly, http://www.mckinsey.com/insights/manufacturing/are_you_ready_for_3-d_printing?cid=other-eml-alt-mkq-mck-oth-1502 (accessed 24 February 2015)

EXHIBIT 6: OBSTACLES TO 3D-PRINTING ADOPTION



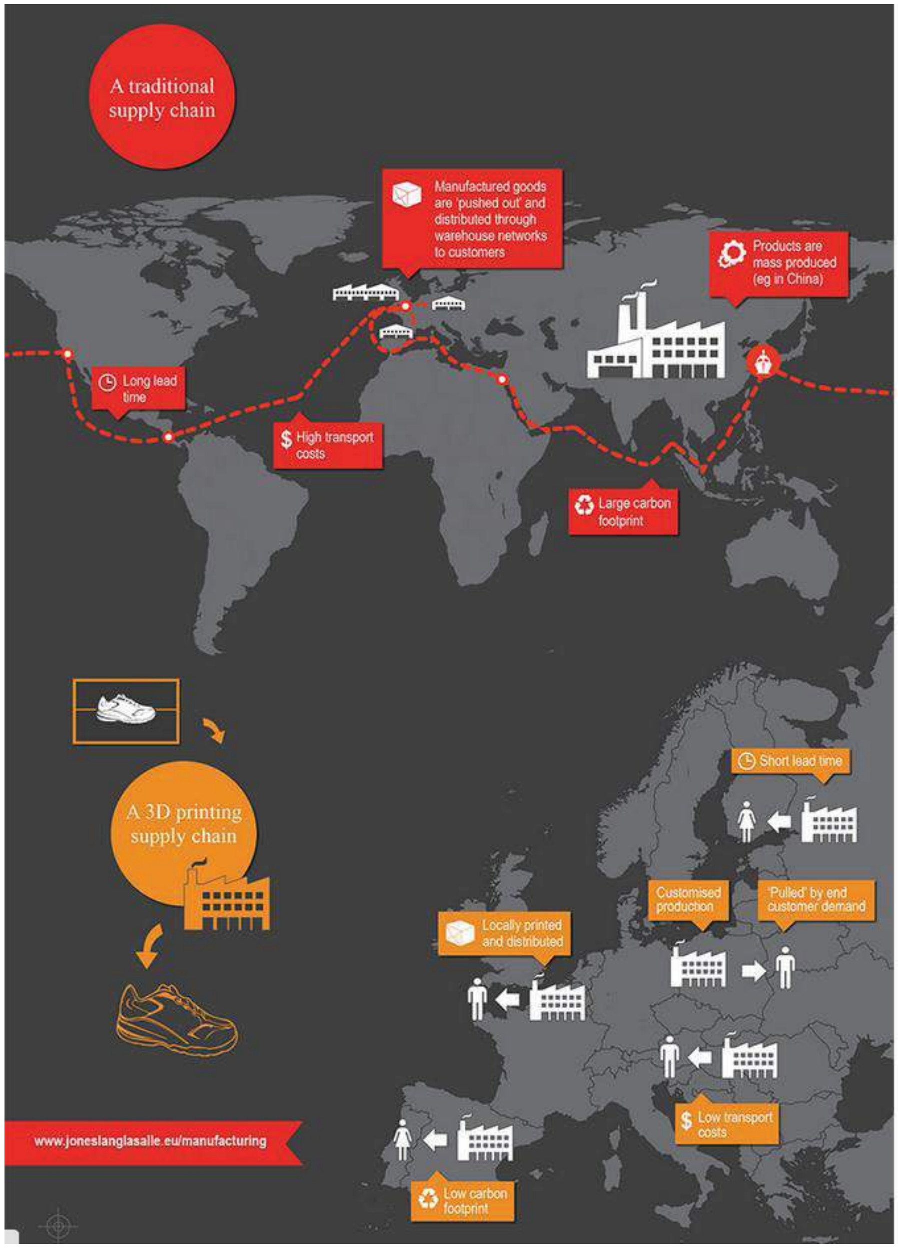
Source: PwC (June 2014) "3D printing and the new shape of industrial manufacturing", http://www.pwc.com/us/en/industrial-products/3d-printing.jhtml (accessed 12 February 2015)

EXHIBIT 7: A TYPICAL SUPPLY CHAIN NETWORK



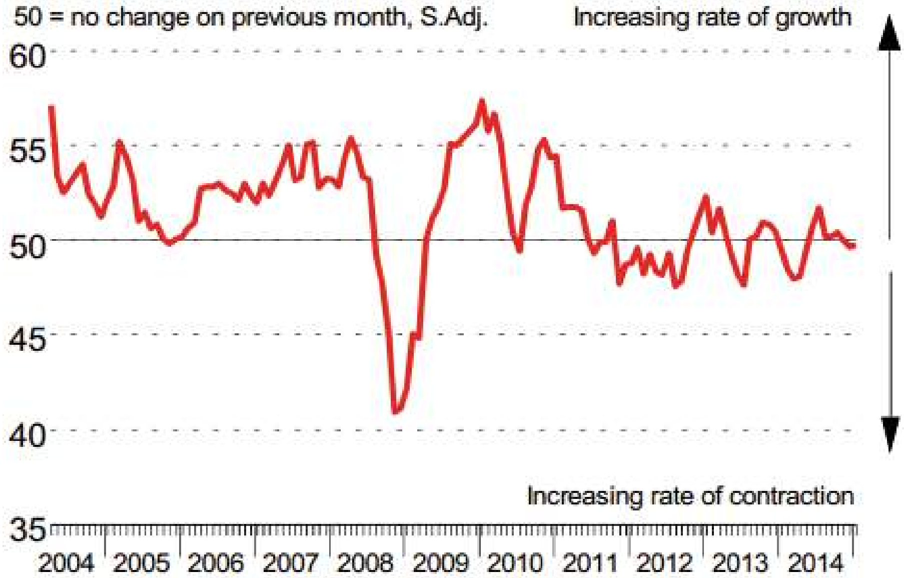
Source: David Simchi-Levi (2007) Designing & Managing the Supply Chain, 3rd edition, McGraw-Hill, pp. 2.

EXHIBIT 8: A COMPARISON OF TRADITIONAL AND 3D-PRINTING SUPPLY CHAINS



Source: Jones Lang LaSalle (2013) "The Evolution of Manufacturing", http://www.jll.eu/emea/en-gb/services/property-types/logistics-industrial/the-evolution-of-manufacturing/infographic (accessed 12 February 2015)

EXHIBIT 9: HSBC CHINA MANUFACTURING PMI 2004-2014



Source: HSBC Purchasing Managers' Index™ Press Release (2 February 2015)

EXHIBIT 10: CHINA'S GROWING 3D-PRINTING ECOSYSTEM

The Chinese 3D printing market is still at an early stage.

In 2013, nearly 60% of China's 3D printer production was for export, while Chinese 3D printer makers shipped only 8,743 printers, generating $33 million in revenue domestically.

The automotive sector was the largest application segment, at $6.8 million in revenue, followed by education with $6.5 million. However, in terms of unit shipments, the consumer market was the largest application segment, with an estimated shipments of just over 5,900 units in 2013.

By 2018, the Chinese 3D printer market (excluding imported 3D printers) will grow to 37,800 units, at a compound annual growth rate (CAGR) of 34%, with printer revenue growing to $109 million in 2018, at a CAGR of 27%. Education is anticipated to lead this growth, although both the automotive and health care sectors will also strengthen.

In terms of printer type, metal 3D printer is forecast to be the fastest growing segment in the next five years, followed by low- to medium-end polymer sector and the industry polymer sector.

Source: Lux Research Inc. (8 September 2014) "China's Growing 3D Printing Ecosystem", http://portal.luxresearchinc.com/research/report_excerpt/17840 (accessed 30 January 2015)