10-021
March 2017

The 3D Printing "Revolution" An Imminent Reality or a Misunderstood Fantasy?

"3D Printing technology has the potential to revolutionize the way we make almost everything" / US President Barack Obama, February 13th, 2013 [1]

A Quick Preface

Futurists and technology visionaries around the world have praised 3D (three dimensional) printing as one of the most significant revolutions known to mankind, predicting that life on Earth will soon radically change because of it.[2] In optimistic scenarios, manufacturers will be able to produce goods domestically, with almost no wasted materials and no need for outsourcing. 3D printing may be executed using almost every material and form, with unconventional uses such as bio-printing organic tissues and organs (note that skin and kidneys have already been 3D printed before) which may extend human life expectancy and improve our quality of living.

However, despite the dreams and high expectations, this technological revolution did not, so far, materialize. 3D printing giants have matured and many market players and contestants have made substantial efforts to bring the anticipated technology to life but so far with limited success. Thus far, this revolution, although technologically probable, seems distant and unlikely, and this case study aims to investigate the promising but lingering (not to say stagnant) phenomenon of 3D printing.

This case was prepared by Dr. Yair Friedman and Shahar Cohen from the Coller School of Management, Tel Aviv University. The case is intended as the basis for class discussion rather than to illustrate either effective or ineffective handling of administrative situations and decisions.

[1] http://www.3ders.org/articles/20130213-president-obama-called-3d-printing-the-potential-to-revolutionize-in-state-of-the-union-address.html

[2] http://www.cnbc.com/2014/05/09/will-3-d-technology-radically-change-the-world.html

Background & History

3D printing, also known as 'additive manufacturing' (AM), is a technology that transforms digital 3D models into solid objects by constructing them up in layers. This technology was invented in the 1980s and has since been mainly used for producing prototypes (a.k.a. rapid prototyping or RP), tooling and manufacturing of unique and inimitable items, for example props in motion films such as Iron Man[3], Guardians of the Galaxy and the Avengers[4] (see Appendix 1 for a more detailed analysis). Since then, 3D printing technologies have evolved and were hailed as a great promise that may revolutionize manufacturing (and consumption) by local, on-demand production of final products (or parts). 3D printing has become a highly-utilized development tool, and in a recent survey by PwC, out of more than 100 industrial manufacturers, two-thirds were already using 3D printing.[5] It is already possible to 3D print in a wide variety of materials, including thermoplastics, thermoplastic composites, pure metals, metal alloys, ceramics and even in various forms of food. As may be expected, North America and Europe account for more than two-thirds of the 3D printing market revenue and Asia Pacific accounts for 27% (2015)[6].

3D Printing process

3D printing includes a wide variety of additive manufacturing technologies, but these build objects in successive layers that are (typically) about 0.1 mm thin. Furthermore, all the various methods start with a computer aided design (CAD) model or a digital scan that is then processed by a software which slices and divides the object into extremely thin cross sections that are then printed out one on top of the other in a variety of materials.

3D Printing technologies

There are several 3D printing technologies[7] which utilize various materials such as semi-liquids, photo-curable resins, powder granules or solids (such as papers, plastics, or metals)[8]. In the near future, 3D printers are expected to handle multiple materials and use multiple print-heads simultaneously. For a detailed technical analysis of printing technologies, see Appendix 2.

1. ***Fused deposition modelling*** ('FDM'). This technology, the most common 3D printing process, is also known as material extrusion, 'thermoplastic extrusion', 'plastic jet printing' (PJP), the 'fused filament method' (FFM) or 'fused filament fabrication' (FFF). It was invented, patented and trademarked by Scott Crump in 1988, and is commercialized by Stratasys (see more about the company below). FDM uses a nozzle to extrude a semi-liquid material to create successive object layers and usually uses a thermoplastic such as acrylonitrile butadiene styrene (ABS), polycarbonate (PC), nylon, or the bioplastic polylactic acid (PLA) but can also use other materials such as thermoplastic composites (mixed with metals, carbon fiber or carbon nanotubes), concrete, clay and many different kinds of foods. Whatever material, it is usually delivered to a

[3] https://www.cnet.com/news/why-hollywood-loves-3d-printing
[4] www.theguardian.com/culture-professionals-network/2015/jun/12/film-technology-evolution-film-making-3d-printing-vr-motion-capture
[5] http://www.pwc.com/us/en/technology-forecast/2014/3d-printing/features/future-3d-printing.html
[6] https://www.ups.com/media/en/3D_Printing_executive_summary.pdf
[7] https://www.iso.org/obp/ui/#iso:std:iso-astm:52900:ed-1:v1:en
[8] http://explainingthefuture.com/3dprinting.html

print head as a solid, thin strand or 'filament' that is then heated into a molten state[9]. FDM technology printers can be purchased for a few hundred dollars although high-end industrial machines still cost hundreds of thousands of dollars but can produce final objects with a comparable quality to injection molded parts. Exemplary manufacturer: Stratasys.

2. ***Stereolithographic 3D printing*** *(known as 'SLA').* This technology was invented and patented by Charles Hull in 1984, who subsequently founded 3D Systems (see more about the company below). Stereolithography, also known as the vat photopolymerization technique, uses a laser or other light source to solidify successive object layers on the base or surface of a vat of liquid photopolymer. Such 3D printers position a perforated platform just below the surface of a vat of liquid photopolymer and then a UV laser beam traces the first slice of an object on the surface of this liquid, causing a very thin layer of photopolymer to harden. This is repeated while the platform is slightly lowered. Alternatively, a projector is used to solidify object layers one complete cross-section at a time (this technique is called 'DLP'). Vat photopolymerization 3D printers are relatively expensive because of the high costs of the utilized resins, but offer very high resolutions and deliver superior surface quality. The cost of the printers varies from a few hundreds of dollars for an industrial-grade 3D Systems machine to a few thousands of dollars for a Formlabs desktop sized printer.

3. ***Material jetting***. This technology uses a print head that sprays liquid layers that are subsequently solidified by exposure to UV light. Material jetting offers high resolution 3D printing, potentially in multi-color and multi-material output by spraying various materials (including metal nanoparticles[10]) from a multi-nozzle print head in changeable combinations. This 3D printing technology is still considered very expensive, with prices of a few hundreds of dollars per Kilogram compared to a few dozens of dollars per kilogram for ABS/PLA filaments (used in desktop FDM printers), but reaches a potentially spectacular resolution, as well as high quality surface finish and layer thickness (for example, the Stratasys J750 printer can fabricate objects out of six different materials (both rigid and flexible) in up to 360,000 colors while maintaining a 0.014 mm (14 micron) layer resolution). Exemplary machines and manufacturers: Stratasys' PolyJet (PJ), 3D systems' MultiJet (MJP).

4. ***Binder jetting.*** This technology uses a print head to selectively spray a material binder (glue) onto successive layers of powder (e.g. durable plastic powder or even bronze, stainless steel or Inconel powder) while both binder and powders may be colored, producing full color output. This 3D printing technology is also considered expensive with prices similar to those of Material jetting (see above) due to materials costs. Exemplary manufacturers: ExOne, 3D Systems.

5. ***Powder bed fusion.*** This technology (also known as 'Direct metal laser sintering' (DMLS), 'Selective heat sintering' (SHS), 'Selective laser melting' (SLM), 'Laser sintering' (LS), 'Electron beam melting' (EBM) or LaserCUSING), uses a laser, electron beam or other heat source to selectively fuse consecutive powder layers of materials such as plastics (e.g. nylon), metals (such as aluminum, copper, steel, iron or titanium) or composite materials. The costs associated are highly determined by the type of powder and material being used, the re-usability of the powder

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[9] http://explainingthefuture.com/3dprinting.html

[10] https://3dprint.com/133777/xjet-nanoparticle-rapid-2016

and the process. For examples, prices for nylon powder currently cost 100-200 per kilogram while titanium powder costs range between 200$ and 600$ (depending on particle size and quality. Yet, the associated process is considered more complex and cumbersome as it requires measures such as vacuum to eliminate powder spread, protective masks and gloves. In addition, the powder chamber is required to cool before the next batch, though vendors like HP and others may come with solutions to alleviate it. The technology can produce parts with a structural strength on par with traditional manufacturing techniques. Exemplary manufacturers: 3D Systems, EOS, HP.

6. ***Directed energy deposition.*** This technology uses a laser or a heat source to fuse a powdered build material into solid metal as it is being deposited (placed) from a nozzle. Build materials include steel, copper, nickel and titanium. The technology is also unique in that it can be used not only to create new parts, but also to fuse metal back on to existing parts, such as worn or otherwise damaged turbine blades[11]. Exemplary manufacturers: Optomec, InssTek.

7. ***Sheet lamination.*** This technology fuses together sheets of cut paper, plastic or metal. The sheets can sometimes be sprayed with color inks to create detailed color models. The main advantage of Sheet lamination 3D printers lies in their cheap material costs (paper, cartons, ….), yet accuracy depends on the sheets thickness. Printers' costs differ between 50$ - 700$ thousand. Exemplary manufacturers: Mcor, Fabrisonic, Highcon.

Expiring Patents

Many of the key patents relating to 3D printing were issued before the turn of the century (for example, the Selective Laser Sintering (SLS) powder-based printing process was developed and subsequently patented by Dr. Carl Deckard and Dr. Joe Beaman in 1984) and have reached, or are soon reaching, the end of their lifespan. Hence, the upcoming years are quickly shaping up to be crucial for 3D printing innovations as advanced technologies are becoming more and more accessible due to the expiration of patents on pre-existing industrial printing processes[12] and this also allows new players, rather than the original developers of the technology, to utilize and improve (lower costs and or increase efficiency) 3D printing processes.

For example, in 2009 the Fused Deposition Modeling (FDM) printing process patent expired and allowed new 3D printer manufacturers such as MakerBot and Ultimaker to enter the market, increasing availability of 3D printing by dropping FDM printers’ prices from over $10,000 to less than $1,000! Other 3D printing processes relating patents are also expiring and various segments are slowly but surely experiencing similar competitive changes.

Market Segments

3D printing has, with time, divided itself into two separate segments: industrial high-end printers, which are mainly (but not only) utilized for high-end functional rapid prototyping (RP) and are targeted at enterprises and 3D printing service bureaus (reside in office environments and priced around $15-25K) and office based desktop printers (a.k.a. low-end printers), which are significantly cheaper, are targeted at private consumers and hobbyists and are generally used for simple, straightforward and low-end form and

[11] http://explainingthefuture.com/3dprinting.html
[12] https://techcrunch.com/2016/05/15/how-expiring-patents-are-ushering-in-the-next-generation-of-3d-printing

fit RP tooling (creation of specially designed tools and equipment). Furthermore, these segments include both products (sale of printers, tuners etc.) and services (utilization of public printers, utilization of open designs, service and maintenance etc. For more details on the products vs. services industry segmentation and growth, see appendix 3.

Due to the patents expiration, note that recent years have seen the proliferation of desktop printers (mainly FDM based) offering many of the higher-end capabilities at somewhat lower prices.

Industrial grade printers. Industrial machines are designed to allow professional users improved and more efficient and rapid design and manufacturing processes. This is done by giving direct and swift access to potentially complex prototypes, allow rapid customization, design testing functional prototyping and process enhancement accelerators. Relevant industries[13] include automotive and industrial manufacturing (e.g. production of spare parts and components or rapid prototyping, form and fit testing), aerospace (e.g. create complex geometry parts not possible with traditional manufacturing), pharma / healthcare (e.g. bio-print tissue-like structures for testing during drug development or develop custom orthopedic implants and prosthetics), retail (e.g. create custom toys, jewelry, games, home decorations, and other products) and sports (for example, create multi-color and multi-material prototypes for product testing). For more information on the growth of this segment, see appendix 4.

Office grade Printers. those machines are designed to allow easy 3D printing in an office environment, and began to emerge in the early years of the millennia. Nowadays, there are more than 300 companies who have sold well over 500,000 3D desktop systems.[14] Desktop 3D printers are low-priced (ranging $300 to $5,000) and often come as kits whereby the user must assemble the printers themselves (assembly often takes between 10 and 40 hours). Most systems are sold assembled at the moment and require that print-heads be cleaned periodically, that beds be properly leveled, and require supervision to minimize errors while high-end printers are fasted, are more reliable and usually require less human interference and handling.

Key players

The Polymers (Plastic) based 3D printing industry is highly dominated by two large players, Stratasys and 3D Systems (for more information, see a comparative Stock Chart in Appendix 5), with many mid-sized players (for example EOS, ExOne and XYZPrinting) and numerous small players and startups. In addition, large 'old-school' printing and technology giants such as HP, Seiko Epson and Lenovo (to name only a few), are also getting more and more active in the 3D printing market and are trying to translate synergies and existing competencies to sales and market shares.

The Metal based 3D printing (the HW vendors part) industry is more balanced with several mid-sized players like EOS, SLM, Concept Laser, 3DS and Arcam, each capturing between 10-15% market share while EOS (privately held) leads the market with an approximate 20-25% market share.

On October 2016, GE announced it has signed an agreement to acquire both German Concept Laser and Swedish Arcam, forming a substantial market player (and becoming second or third in size in the metal 3D printing market).[15]

13 http://www.pwc.com/us/en/technology-forecast/2014/3d-printing/features/future-3d-printing.html
14 http://blog.luxexcel.com/desktop-pro-industrial-3d-printers-whats-the-difference
15 http://www.reuters.com/article/us-ge-3dprinting-sweden-idUSKCN12R0LC

Stratasys

Stratasys was founded in 1989, and has sold its first product, the 3D Modeler, in April 1992. In 1994 the company went public on NASDAQ and soon became one of the market leaders in 3D printing worldwide. In the first decade of the millennia, Stratasys was the world unit market leader, suppling more additive fabrication systems worldwide than any other market player[16]. In 2012, Stratasys merged with Israeli competitor Objet Ltd., and is since maintaining dual headquarters in Rehovot (Israel) and Eden Prairie, Minnesota (US). Stratasys produces AM systems and materials and operates a network of AM service facilities in several locations, mainly in the US. One of its main strategic tools for market growth and expansion is mergers and acquisitions and it has acquired numerous competitors and complementary companies, such as Solidscape (2011)[17] and Objet[18] (2012). In August 2013, it acquired Makerbot Ltd. for approximately $400M and during 2014 acquired two of the largest AM service bureaus in the US: Solid Concepts and Harvest Technologies for 350M$ total (upon achieving certain business goals). SolidConcept and Harvest were merged with the legacy Stratasys parts services - RedEye, jointly branded as Stratasys Digital Manufacturing (SDM) with 2015 revenues estimated around 100M$. In September 2014, it announced the acquisition of GrabCad, a Leading 3D CAD Collaboration Platform for an undisclosed amount (estimated at about $100M). However, in accordance with the decreasing market valuations in 2015, Stratasys wrote-off almost $1 Billion of the acquisitions and recognized a 1.37B$ loss in 2015. For more details on Stratasys 2015 financials, see Appendix 6a.

Stratasys printing systems utilize 3 key different technologies: FDM, Polyjet and Wax jetting along the following product lines (in addition to Replicator series attributed to its acquired subsidiary Makerbot):

- Idea Series (Low end): The Idea Series includes lower capacity, affordable set of 3D printers for professional use. This series comprises the MoJo and uPrint product families, both of which are FDM-based. These products are designed for easy use in an office environment and produce professional grade parts using ABS line of thermoplastics.

- Design Series (Mid-range): Design Series includes the Dimension and Objet brands. The Dimension brand features FDM technology and the Objet brand features PolyJet technology. The technology available in this series makes it suited for Rapid Prototyping, from design visualization and communication to form and fit verification to model building for functional testing. The Dimension product line allows users to create parts in ABSplus plastic. This material enables production of parts with the strength required for true form, fit and functional testing.

- Production Series (High-end): The Production Series includes Fortus, Connex and Solidscape brands, The PJ line (Connex and J750) are multi-material 3D production systems, which combine different material properties in the same part, in a single print thus gaining versatility. The FDM line (Fortus) enables to create durable, production-grade thermoplastic. When the part is complete, the soluble or breakaway support material is removed, leaving an accurate, durable part that's environmentally stable. The Solidscape line combines patent-protected, SCP thermoplastic ink-jetting technology and high-precision milling of each layer Objects created with these systems feature extremely high pattern resolution and accuracy and are used primarily for jewelry products and dental applications.

[16] http://investors.stratasys.com/releasedetail.cfm?ReleaseID=598993
[17] http://investors.stratasys.com/releasedetail.cfm?releaseid=599807
[18] http://www.globes.co.il/en/article-1000741478

MakerBot Replicator series:

- MakerBot Replicator series represents desktop 3D printers, compact, and professional-grade 3D printers. Desktop and compact 3D printers are affordable, and designed for easy, desktop use and are typically used by individuals operating alone or within an enterprise. Larger, professional 3D printers have large build volumes, ideal for industrial prototypes, models and products. In addition to the Replicator 3D printer series, the MakerBot portfolio includes the Digitizer, which is a 3D scanner that allows customers to scan an object and convert it into a digital file that can be subsequently printed.

3D Systems (3DS)

3DS became the first company to commercialize AM when it sold its first stereolithography (SLA) system in 1988 and sold its first material jetting system, multi-jet (MJ) modeling, in 1996. While extending and enhancing its SLA product line, 3D systems acquired along the years a wide-variety of AM technologies.

In 2001, it acquired DTM Corporation and its selective laser sintering (SLS) polymer powder bed fusion technology. In 2011 it acquired Z-Corp., with its binder jetting technology. 3DS also made significant strides into the metal AM arena in 2013 when it acquired Phoenix Systems and its metal powder bed fusion technology as well as LayerWise (Metal AM) in 2015. During 2014 3D Systems spent $345M in a series of acquisitions of service providers: Medical Modeling, Robtec, Laser Reproductions, and American Precision Prototyping. 3D Systems completed its acquisition of CAD/CAM software company Cimatron in February 2015 for about $97M. In total, 3DS acquired 25 companies in 2013 (4 businesses), 2014 (10 businesses) and 2015 (11 businesses) alone. For more details on its financials, see Appendix 6b.

3DS offers 3 main machines product lines:

- Desktop: Includes the FDM based CuboPro and micro-SLA Projet 1200. On Dec 2015, 3DS announced that it will discontinue production of its $999 consumer 3D printer, the Cube. This move evidently reflected its management plans to focus resources on near-term opportunities and profitability while availability of the company’s CubePro 3D print, designed for desktop engineering, educational and professional applications was untouched.

- Professional: consists of multi-jet machines (MJP) aimed for rapid prototyping, the CJP line (based on the Z-corp acquisition) utilizes binder jetting technology which is capable to create colorful models and mid-range SLA.

- Production: Industrial machines, used in the largest services bureaus and production environments, consist of high-end SLA, SLS and Direct Metal Printing (DMLP/DMLS) machines. According to various estimates, this Production line is the backbone of 3DS, contributes the lion share of revenues and gross profit.

Quickparts and software (SW)

The company also offers service bureau line of business, branded as Quickparts, with revenues estimated at around $110M. Quickparts offers a global on demand parts service and operates its proprietary instant online quoting engine. Further, the company offers SW product lines resulting from the acquisition of CAD/CAM vendor Cimatron (2015 revenues ~45M$) and Simbionix, a provider of innovative training and education solutions for medical professionals and the healthcare industry.

Other players

There are literally hundreds of mid- and small- sized market players (as examples, we present EOS as a mid- sized player and Xjet as a small player). Niche mid- and small- sized players usually focus on a limited number of markets and seek to acquire market share through development of proprietary technologies. They mostly focus on the US, the world's leading market for 3D printing (with approximately 38% of the total worldwide 3D printing industry market share), but may also target Japan (9.7%), Germany (9.4%), China (8.7%), the UK (4.2%), Italy (3.8%), France (3.2%) or South Korea (2.3%).[19]

EOS. EOS is a German 3D printing technology manufacturer, considered to be among the largest 2nd tier players (after Stratasys and 3DS). EOS is active in most 3D printing technologies, having developed industrial solutions encompassing stereolithography, SLS powder sintering, DLMS powder sintering, and more.

Xjet. XJet is an Israel-based 3D printing company focused on creating metal parts for manufacturing purposes by employing sealed cartridges of liquid material. While other metal printers rely on dust filings which are loaded into the printer by hand, XJet has pioneered the use of liquid metal as a more affordable alternative.

'Paper and Ink' players

Hewlett-Packard (HP) has been developing 3D printing technology since 2013[20]. HP first ventured into the 3D printing space through a partnership with Stratasys, which was created in 2010 to produce HP-branded 3D printers. The partnership ended in 2012 and since then HP has been developing various 3D printing technologies, among others, utilizing glass as a potential candidate. HP claimed that its new 3D printing technology will be 10 times faster than that in existing 3D printers, will be more affordable and will print stronger products than current market offerings. With those improvements, HP claims it can make 3D printing much more widely adopted than it is today.[21] Seiko Epson has also expressed an interest in 3D printing and Epson CEO Minoru Usui claimed (2011) that the company was developing a 3D printer and that in a few years it will be possible to print on demand in 3D.

[19] http://www.inside3dp.com/four-countries-emerging-3d-printing-giants

[20] http://www.mercurynews.com/2013/10/23/biz-break-hewlett-packard-developing-3d-printers

[21] https://www.cnet.com/news/hp-unveils-multi-jet-fusion-3d-printing/

What lies ahead?

Printing efficiency, speed and related costs

3D printing technology is expected to increase in efficiency and speed[22]. Nowadays, 3D printing usually takes hours and sometimes days and in some cases required human interference. But while companies are improving printers incrementally, new methods and designs are expected to improve efficiency and speed by using higher-quality components, increasing printer autonomy and optimizing structures (e.g. laser movements). Finally, printer costs are still relatively high as are materials costs and availability. These are expected to drop as soon as 3D printers evolve and become more and more commonly utilized.

Changing value chains

By allowing the end users to print their own designs or reproduce existing ones, current value chains may be in dire need to adapt and market players (such as manufacturers and retailers, to name only a few) must adjust or perish[23]. Issues such as IP management, ideation, manufacturing rights, trade marks, logistics and marketing arrangements may require substantial modifications and regulation.

3D printing opportunities and directions[24]

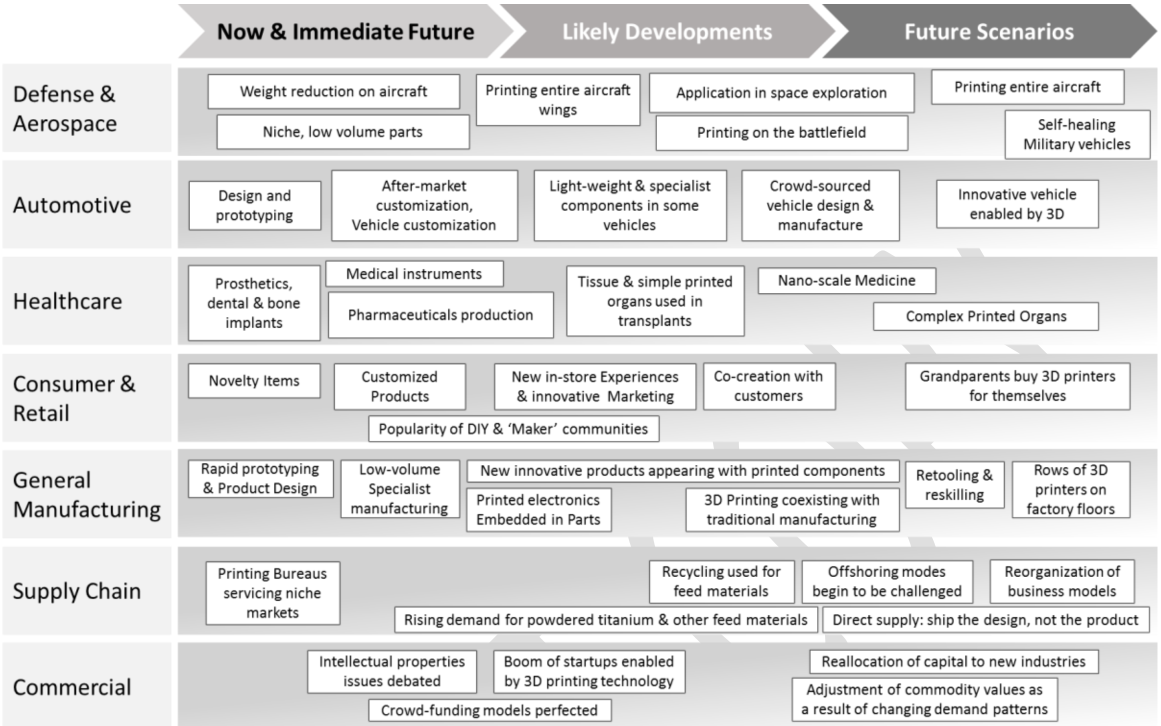
In recent years, several unexpected changes and declarations were issued by interested parties. In 2014, Amazon opened an online 3D printing store, where customers shop for products that can be 3D printed, opening and simplifying the design process for interested users, mainly in the desktop printing segment. This move has resulted in rival online 3D printing stores such as 3DLT moving business into the Amazon platform or closing shop soon thereafter. Also in 2014, retail giant Home Depot declared it will start selling Stratasys and Makerbot printers throughout the US, providing unprecedented access to potential small as well as private clients. Lastly, companies in both the automotive and aerospace industries have given presumptuous declarations on the use of 3D printing: US motor vehicle manufacturing company Local Motors which focuses on low-volume manufacturing of open-source motor vehicles launched a 3D printed car challenge in 2014 (three years before that, Stratasys has built Urbee, a prototype Car with an entire body created in 3D printing[25]) and in parallel, BAE Systems declared it is developing a futuristic military aircraft with on-board 3D printers and robotic assembly machinery that can create different on-demand drones.[26] While the 3D printing industry seems to be maturing rapidly, such industry changes and conjectures demonstrate that there are still numerous changes to come.

Transition from RP to manufacturing

Manufacturing (a.k.a. end-use parts) is considered to be the holy grail of 3D printing, whereas today the lion share of 3D printing is aimed at RP applications. Yet, it is estimated that the RP segment is approaching maturity, and it remains to be seen if manufacturing markets ever evolve, enabling

[22] https://www.pwc.com/us/en/technology-forecast/2014/3d-printing/features/future-3d-printing.html
[23] https://www.atkearney.com/documents/10192/5992684/3D+Printing+A+Manufacturing+Revolution.pdf/bf8f5c00-69c4-4909-858a-423e3b94bba3
[24] http://www.3ders.org/articles/20140904-the-10-most-influential-companies-and-executives-in-3d-printing.html
[25] http://www.stratasys.com/resources/case-studies/automotive/urbee
[26] http://www.baesystems.com/en-uk/feature/aircraft-technologies-of-the-future

production of completed parts, systems and products such as aircrafts, vehicles, electrical appliances and consumer goods[27]. The following diagram illustrates potential developments and scenarios[28] :



As illustrated, materials costs and properties (mainly Polymers), as well as machines productivity are still better than legacy techniques such as casting, injection molding or vacuum forming. Still, 3D printing is already used to create molds, patterns and layups for various manufacturing techniques. Some industry stakeholders such as HP believe that 3D printing may be suitable for short-runs of few hundreds to few thousand of production units. Moreover, it may be possible that similar to digital 2D printing, the decrease in price per 3D printed part will allow 3D printing to replace legacy manufacturing and will make economic sense in both small and medium sized quantities. Note that metal 3D printing is already being used for manufacturing applications (mainly Aerospace, Automotive and Medical) rather than RP applications. As a result, metal 3D printing is growing rapidly (See appendix 7 for more info on the Metal 3D printing market), and mentioned GE acquisitions is a clear vote of confidence in the long-term prospect of metal 3D printing.

Designed for Additive Manufacturing (DfAM)

One of the most affected processes is one of design. Designing for additive manufacturing processes (DfAM) is potentially different than traditional design for manufacturing processes because the 3D printing process is unlike that of traditional machining, casting, or injection molding. DfAM concerns itself with the best practices to allow for optimal manufacturing with the goal of keeping costs down. It

[27] Leading Edge Forum (LEF) Global Research, 2016
[28] http://lef.csc.com/assets/3705

achieves this by addressing concerns early in the design phase, so they don't cause issues further downstream in the manufacturing process. Designing 3D prints does not necessarily have to take into consideration traditional formations, tooling costs, form complexities or materials and allows effective production of formerly difficult or even impossible parts. In 2013, GE and GrabCAD launched a 3D Printing Design Quest, named the GE bracket challenge.[29] The challenge offered a $7,000 cash prize to the best design of a metal jet engine bracket with the aim of achieving a 30% lighter bracket. However, the winning design achieved 84% (!) decrease in weight while preserving integrity and mechanical properties (such as stiffness).

Summary

Although there is still a lot of hype surrounding 3D printing and how it may or may not be the next industrial revolution, one thing is certain: the cost of 3D printing will continue to decrease while its quality will continue to improve. However, it is still uncertain whether the desktop market can in fact grow or whether the promise lies in the commercial market (in prototyping and production), as HP CEO Dion Weisler claimed in 2016 when interviewed for Fortune magazine[30]. Another question revolves around entrance of new market players in the form of "old school printing giants" such as HP or Seiko Epson, interested in moving away from the declining market of paper-and-ink printing, potentially by acquisitions[31]. 3D printing as an end-use manufacturing technology is still very much in its infancy, and while some industries already heavily rely on 3d printing (e.g. 98% of hearing aids worldwide are manufactured using 3D printing[32]), most industries are slow to embrace 3D technology. But in the coming decades, and in combination with synthetic biology and nanotechnology, we ask ourselves whether 3D printing has the potential to radically transform design, production and logistics processes.

Case Questions

1. Is 3D printing truly a disruptive phenomenon in your opinion? Will it co-exist with or eradicate existing business models and industries? Explain. Pay specific attention to the question of value creation - who creates the value and who owns it? Who experiences the outcomes and side effects?

2. Do you expect any industries to be untouched by 3D printing? If so, describe one such example in detail.

3. Can desktop 3D printing thrive? Explain.

4. If you were the CEO of one of the industry players, how would you proceed? What are the options facing leading vendors (3DS, Stratasys etc.) given the proliferation of low-end, low cost alternatives?

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29 http://www.gereports.com/post/77131235083/jet-engine-bracket-from-indonesia-wins-3d-printing
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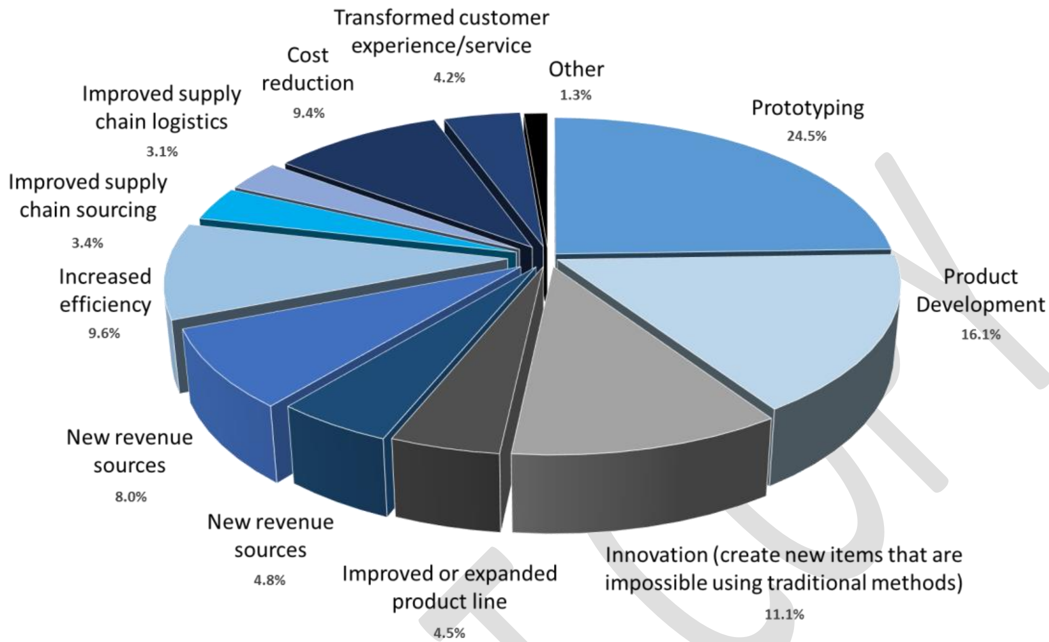
http://www.3ders.org/articles/20140904-the-10-most-influential-companies-and-executives-in-3d-printing.html
http://www.stratasys.com/resources/case-studies/automotive/urbee

Appendices

Appendix 1: Reasons for Pursuing 3D Printing[33]



Source: Gartner, 2014

33 http://www.gartner.com/newsroom/id/2940117

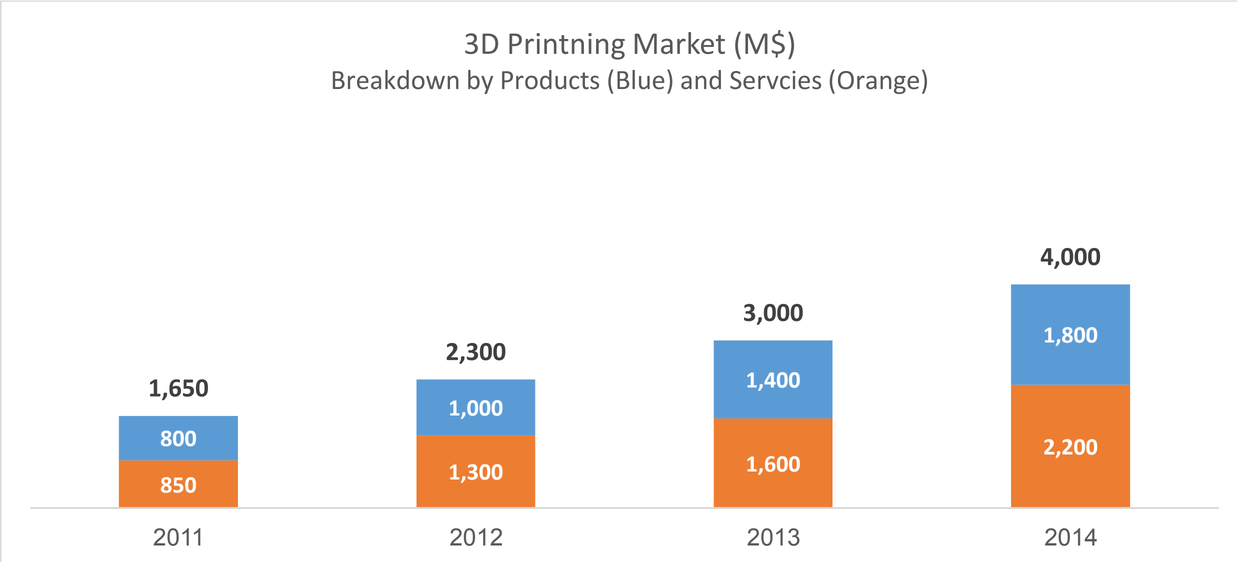
Appendix 2: Comparison of Key Techniques

Process	Description	Details	Advantages	Disadvantages High HW Costs	Applications
Selective Laser Sintering (SLS)	Laser fusion in a powder bed	Layers : 0.06-0.15 mm Features : 0.3mm Surface : rough Print speed : fast	Strong Complex parts Large build volume Parts can be stacked in build volume Variable cost relatively cheaper	Grainy surface finish High HW Costs Parts requires cooling - productivity hinder Dusty, messy enviornment - requires separate room and protective wear	Electronics housing Mounts Custom consumer products Aerospace hardware
Stereolithography (SLA)	UV laser scanning vat polymerizatio n	Layers : 0.06-0.15 mm Features : 0.1mm Surface : smooth Print speed : average	Fine detail Smooth surface finish High productivity	Weak parts Susceptible to sunlight and heat Hazardous material	Medical/dental products Electronics casings Investment casting patterns Art
Binder Jetting (BJ)	Particle binding in a powder bed	Layers : 0.089-0.12 mm Features : 0.4mm Surface : rough Print speed : very fast	Multicolor prints Fast print speed	Very weak parts Rough surface finish	Full color prototypes and objects Figurines
Poly-jet (PJ) / Multi-Jet (MJ)	Jetted droplets of UV cross-linked polymer	Layers : 0.016-0.032 mm Features : 0.2mm Surface : smooth Print speed : fast	Fine detail High accuracy Multi-material capabilities	Low material strength Susceptible to sunlight and heat	Medical devices Complex and multi-material prototypes and objects Assembled prototypes
Fused Deposition Modeling (FDM)	Extruded layers of thermoplastic	0.1-0.3 mm layers Surface : very rough finish Print speed : slow	High part strength Low cost	Poor surface finish Slow printing Medicore resolution	Electronics housing Mounts Custom consume

Source: Sculpteo, edited by the authors[34]

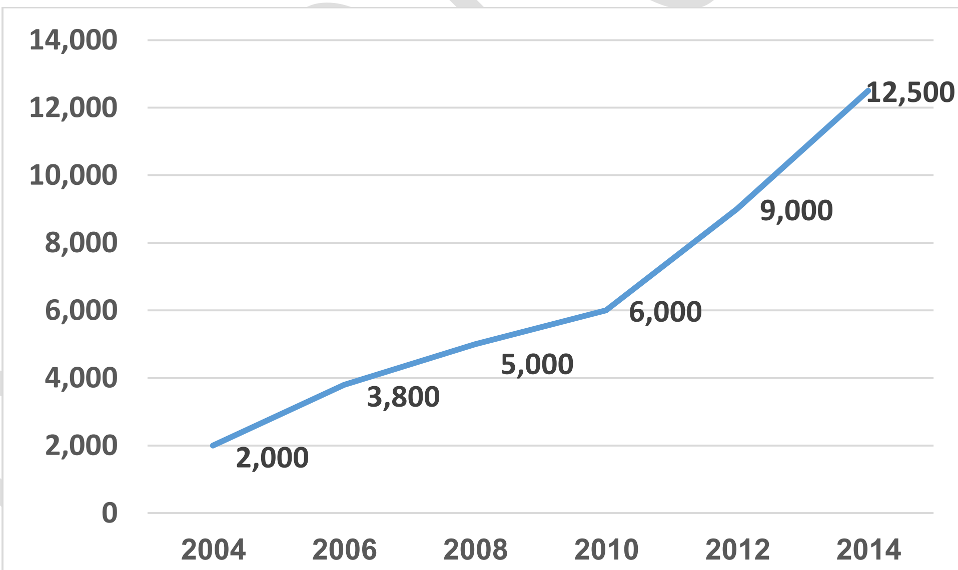
[34] See elaboration including videos and graphics here: https://www.additively.com/en/learn-about/3d-printing-technologies; http://3dprintingfromscratch.com/common/types-of-3d-printers-or-3d-printing-technologies-overview

Appendix 3: 3D Printing Market (M$), breakdown by Products & Services



Source: Wohlers Associates ,2015

Appendix 4: Industrial 3D Printing (5000$+) Market (units)



Source: Wohlers Associates ,2015

Appendix 5: Comparative Stock Charts of Stratasys Ltd. vs. 3D Systems Corporation

Source: Nasdaq, 2016

Appendix 6a: Key figures from Stratasys 2015 annual report (20-F)

	Year Ended December 31,		
	2015	2014	2013
	(U.S. $ in thousands, except pe		
Statement of Operations Data:			
Net sales	$ 695,995	$ 750,129	$ 484,403
Gross profit	102,172	362,394	226,173
Research and development expense, net	122,360	82,270	52,310
Selling, general and administrative expense	434,619	351,993	202,040
Goodwill impairment	942,408	102,470	-
Change in fair value of obligations in connection with acquisitions	(23,671)	(26,150)	754
Operating income (loss)	(1,373,544)	(148,189)	(28,931)
Net income (loss)	(1,373,511)	(119,470)	(26,907)
Net income (loss) attributable to Stratasys Ltd.	(1,372,835)	(119,420)	(26,954)
Net income (loss) per basic share	(26.66)	(2.39)	(0.64)
Net income (loss) per basic share attributable to Stratasys Ltd.	(26.64)	(2.39)	(0.64)
Weighted average basic shares outstanding	51,592	50,019	42,079
Net income (loss) per diluted share	(26.66)	(2.39)	(0.68)
Net income (loss) per diluted share attributable to Stratasys Ltd.	(26.64)	(2.39)	(0.68)
Weighted average diluted shares outstanding	51,592	50,019	42,099
Balance Sheet Data:			
Working capital*	$ 374,346	$ 546,062	$ 714,404
Total assets*	1,414,356	2,899,107	2,782,221
Equity	$ 1,188,801	$ 2,531,239	$ 2,499,787

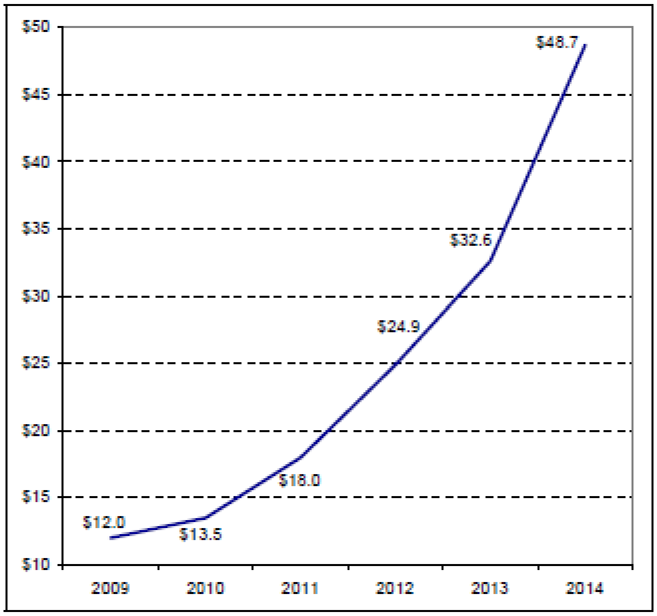
Source: Stratasys website

Appendix 6b: Key figures from 3DS 2015 annual report (20-F)

Consolidated Statements Of Operations And Comprehensive Income (Loss) - USD ($) $ in Thousands	12 Months Ended		
	Dec. 31, 2015	Dec. 31, 2014	Dec. 31, 2013
Revenue:			
Products	$ 408,119	$ 442,198	$ 356,032
Services	258,044	211,454	157,368
Total revenue	666,163	653,652	513,400
Cost of sales:			
Products	243,639	223,991	159,628
Services	130,715	112,227	86,178
Total cost of sales	374,354	336,218	245,806
Gross profit	291,809	317,434	267,594
Operating expenses:			
Selling, general and administrative	303,784	215,724	143,244
Research and development	92,770	75,395	43,489
Impairment of goodwill and other intangible assets	537,179		
Total operating expenses	933,733	291,119	186,733
Income (loss) from operations	(641,924)	26,315	80,861
Interest and other expense, net	13,029	8,928	16,855
Income (loss) before income taxes	(654,953)	17,387	64,006
Provision for income taxes	8,972	5,441	19,887
Net income (loss)	(663,925)	11,946	44,119
Less net income (loss) attributable to noncontrolling interests	(8,433)	309	12
Net income (loss) attributable to 3D Systems Corporation	$ (655,492)	$ 11,637	$ 44,107
Net income (loss) per share available to 3D Systems Corporation common stockholders — basic and diluted	$ (5.85)	$ 0.11	$ 0.45

Source: 3DS website

Appendix 7: Metals 3D Printing Market (M$)



Source: Wohlers Associates ,2015