ADDITIVE MANUFACTURING OR 3D PRINTING AND ITS ADOPTION

HARM-JAN STEENHUIS
Eastern Washington University, Department of Management, USA
hsteenhuis@ewu.edu (Corresponding)

LEON PRETORIUS
University of Pretoria, Department of Engineering and Technology Management

Graduate School of Technology Management, South Africa
Leon.Pretorius@up.ac.za

ABSTRACT

This study is on additive manufacturing, also known as 3D printing. Additive manufacturing is different from traditional manufacturing processes that shape products through milling, grinding etc. Instead, with additive manufacturing, layers are added to a product. This allows for three dimensional manufacturing and limited scrap. Additive manufacturing has been viewed by many as a disruptive innovation for society because it allows consumers to manufacture their own products. In this paper, an overview will be presented on the status of additive manufacturing. This includes the consumer perspective as well as the manufacturing perspective. For example, the consumer perspective has intellectual property protection as an emerging issue. The current status of 3D printers will be provided together with an analysis of the main producers such as Makerbot and Ultimaker (consumer markets) and Stratasys and 3D Systems (industrial markets), their models and their current capabilities and overall adoption. It is concluded that additive manufacturing is experiencing high growth but that, in particular for industrial applications, it is not yet competitive with traditional manufacturing systems.

Key words: Additive manufacturing, 3D printing, technology diffusion, innovation.

INTRODUCTION AND RESEARCH METHOD

If you have been following any news on technology development then it is hard to have missed the hype about 3D printers. It is often described in terms of the Star Trek replicator, see for example Budmen and Rotolo (2013), O'Rourke (2013) and Zhang (2013) and it is touted as going to be one of the most disruptive technologies. Sung-Won (2013) lists it among the top-seven disruptive innovations, Hyman (2011) among the top-10 technologies that will transform the next decade. It is viewed as disruptive for manufacturing (Merrill, 2014) as well as service (Soubra, 2013) although some wonder how disruptive it is really going to be (Dawson, 2014).

The purpose of this paper is to gain insight into 3D printing by following an exploratory research approach. Three research questions were formulated.

1. What methods exist for 3D printing?

2. What are current 3D printing companies?

3. How is the market for 3D printing developing?

The research method used in this paper is essentially exploratory in nature. Literature review and other secondary company data are used in the research to inform some of the research questions posed here. Furthermore Bibliometrics is used to address the initial approach to answering in some sense the question about 3d Printing market development. The ensuing sections of the paper are structured to address the above mentioned research questions in the field of 3D Printing technology.

METHODS FOR 3D PRINTING

In most common form of 3D printing is additive manufacturing (Budmen and Rotolo, 2013) although increasingly the two terms are used interchangeably (Barnatt, 2013). Additive manufacturing is the process of building up an object in a great many layers (Barnatt, 2013). There are a few key characteristics of this process that stand out compared to 'traditional' manufacturing methods. First, since it builds up a product one layer at a time it is possible to manufacture, in one step, a product that contains movable parts or contains other objects inside it. This is not possible in traditional manufacturing. Second, since it is building up one layer at a time, it is possible to manufacture, in one step, hollow-products. This is, for example, not possible in traditional metal processing where material has to be removed from a metal piece which leads to waste. Third, since it is processed in small layers from a digital design, it is possible to produce a product without the need of a mold. This is, for example in traditional plastic injection molding not possible and instead an expensive jig or tool is required. Fourth, due to the combination of the design software and no need for a mold and the ability to produce one unit, it has made manufacturing a possibility for persons who previously needed a manufacturing background and the ability to buy expensive equipment in order to produce something. This is one of the reasons why 3D printing is often considered a disruptive technology. There are essentially three different methods for 3D printing, see figure 1, although there are some variations.

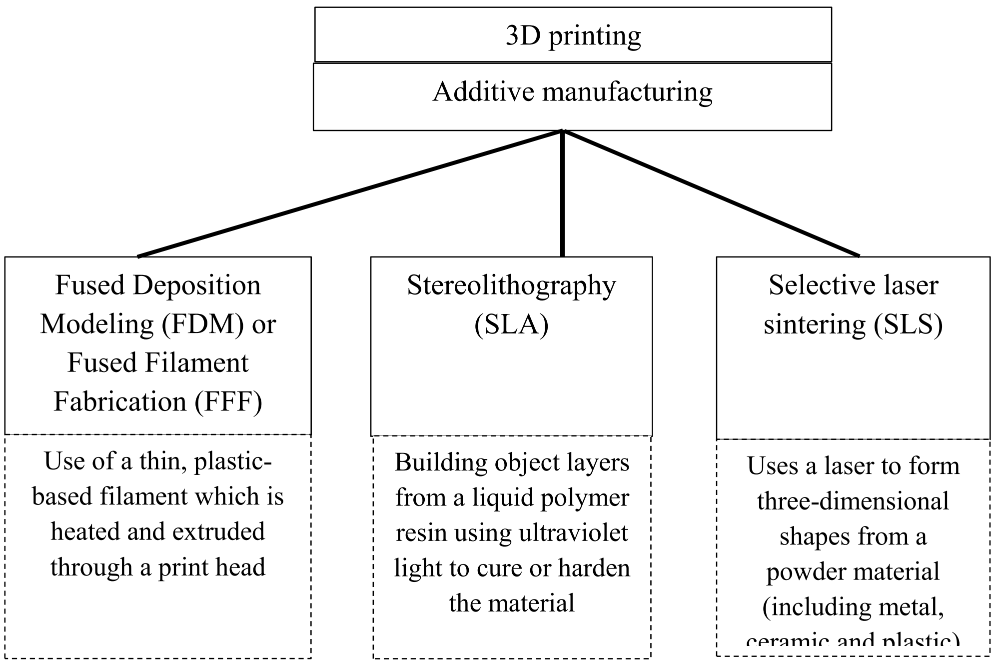

Figure 1: Additive manufacturing techniques, Source: based on Budmen and Rotolo (2013)

“Fused Deposition Modeling (FDM) is a material extrusion 3D printing process that creates objects in layers by depositing a heated thermoplastic from a computer-controlled print head nozzle. FDM was invented by a company called Stratasys, which has trademarked the term. Other companies subsequently refer to this type of technology as plastic jet printing (PJP), fused filament modelling (FFM), fused filament fabrication (FFF), the fused deposition method, or simply thermoplastic extrusion.” (Barnatt, 2013: 225). This type is most similar to the regular inkjet 2D printer. There is material, similar to the inkjet cartridge, although in this case it is often a type of plastic and it comes on a spool, similar to what you may find in a weed wacker. The material is led through the printer head and is heated so that it melts. It is then spread on the surface similar to the printing of letters. However, in this case, additional layers are put on top of each other, similar to printing the same letter on the same spot of paper over and over again so that the ink layer becomes thicker and a noticeable three dimensional structure appears. Aside from plastics, this technique can also be used for metals, wood, concrete and even chocolate (Barnatt, 2013). Another modification is multiphase jet solidification (MJS), that is, ceramic or metal powders are mixed with a ‘binder’ to create a filament strand that can be 3D printed using roughly the same process as FDM (Barnatt, 2013). One disadvantage of the FDM technology is that it can be slow. There is also a possibility of warping and shrinking of the products as a result of the cooling down process.

Another technology is stereolithography. “Stereolithography is a 3D printing technology that builds objects in layers using a so-termed StereoLithographic Apparatus (SLA). Stereolithography is based on photopolymerization, with a laser beam used to trace out and solidify each successive layer of an object on the surface of a vat of liquid photopolymer.” (Barnatt, 2013: 234). This process is quite a bit different than the FDM process. Here, there is essentially a container with a chemical liquid. A print bed is near the top of the container so that only a small layer of the liquid is on top of it. This layer is then exposed to light, typically a laser, which then solidifies it thereby creating a first layer of material. The print bed is then lowered a tiny fraction so that another thin layer of the liquid goes on top of the material that was just formed and the process repeated. Similar to FDM, the product is therefore produced one layer at a time. An alternative is digital light processing (DLP). With this technology a DLP projector is used to selectively solidify a polymer liquid (Barnatt, 2013). Another alternative is two-photon polymerization (2PP). This is a ‘nanophotonic’ 3D printing method that is very similar to stereolithography but working on a very small scale (Barnatt, 2013). An advantage of SLA is that the products that are produced with this method are smoother but a disadvantage is that it is a more expensive technology and it requires the handling of chemicals.

The third technology is selective laser sintering. “Selective laser sintering (SLS) is a powder bed fusion 3D printing technology that uses a laser to selectively fuse or ‘sinter’ together the granules of successive layers of powder.” (Barnatt, 2013: 232). This process has some similarities with the SLA process but instead of a liquid, it uses powder. Thus, a thin layer of powder lies on top of a build surface. A laser is used to trace the shape of the object and then the build platform is slightly lowered, a new thin layer of powder is placed on top of it and the process is repeated. Another method that similarly uses powder is binder jetting.

A fourth, quite different technique, is laminated object manufacture (LOM). “LOM builds objects in layers by sticking together laser-cut sheets of paper, plastic or metal foil. In the LOM process a feed mechanism advances a thin sheet of material onto the build platform. The material either has an adhesive backing or at this stage has adhesive applied. A roller (sometimes heated) then passes over the sheet to press it into place. A laser finally cuts the outline of an object layer into the sheet, and the build platform lowers just a little. The process then repeats until all object layers have been created." (Barnatt, 2013: 68).

In addition to these three main technologies for 3D printing there are other methods that present slight modifications. For example Barnatt (2013) mentions directed energy deposition, electron beam melting, selective heat sintering, and material jetting. In the last case a liquid photopolymer is emitted from a multi-nozzle, inkjet-style print head to form an object layer, and is then set solid with UV light before the next layer is added. Other names for this process are polyjet, polyjet matrix, multi jet modelling (MJM) or inkjet photopolymer.

CURRENT COMPANIES AND THEIR PRODUCTS

The current companies and their products will be discussed in this section. The discussion is separated into consumer products and industrial products.

Consumer market

The 3D consumer printing industry is in an early, turbulent, stage of development and undergoing many changes. In some ways, it resembles the early home computer market where several technology-oriented hobbyists were building their own home computers. Some of these entrepreneurs were successful in launching their computers into the market such as the ZX Spectrum and the Commodore 64 and numerous clones were also produced. The industry was in flux and product improvements such as improved memory and video cards were all part of the innovative climate at the time. Similarly, the 3D consumer printing industry is in a lot of flux, there are many hobbyists and entrepreneurs and there are many product introductions. "It is believed that more than 250 companies and teams are making personal 3D printers, with a few that generated revenues of $1 million or more within a year of launch" (Wohlers Associates, 2014: 99). There are many product innovations such as improvement in build volume, print accuracy, print speed, dual extruders (allowing more colors), heated platforms to prevent warping, etc. This state of flux does not only characterize development and manufacture of consumer 3D printers but also for example design software companies (dealing with scanning technologies, CAD etc.), 3D-printed designs (providing object designs) and service bureaus (providing access to 3D printers). Table 1 provides an overview of some of the active companies that manufacture consumer 3D printers.

One of the most recent introductions is from Dremel. In September 2014 this tool manufacturing company introduced its 3D Idea Builder (Mearian, 2014). Some companies, such as MakerBot have their own retail stores. Several other companies have aligned themselves with chains such as Home Depot or Staples where their printers are now being sold. In 2013, while growing by 104.2% compared to 2012, an estimated 72,503 machines were sold for an average price of $1208 while cumulatively for the last six years the number is 140,425 units (Wohlers Associates, 2014). Bashir (2014), based on cumulative units sold and including only the top consumer-oriented companies estimates the market share as shown in figure 2.

Table 1: Consumer 3D printer companies

Sources: Barnatt (2013), Lipson and Kurman (2013), Wohlers Associates (2014), company websites

Company	Location	Example products
3D Systems	USA	CubeX, ProJet 1200
Aleph Objects	USA	Lulzbot TAZ
Asiga	USA	Freeform Pico 2, Freeform PRO
Delta Micro Factory Corporation (PP3DP UP! and Afinia)	China	UP! Plus/Afinia H series
Deezmaker	USA	Bukito, Bukobots
Fabbster	Germany	Fabbster G
Felix robotics	Netherlands	Felix 3.0
Flashforge	China	Dreamer, creater
FormLabs	USA	Form 1
German RepRap	Germany	Protos X400, Neo
Hyrel	USA	System 30
Leapfrog	Netherlands	Creatr
MakerGear	USA	M2
Mcor Technologies	Ireland	Matrix 300+
Portabee	Singapore	Portabee GO
Printrbot	USA	Printrbot Simple
Solidoodle	USA	Solidoodle press, Solidoodle 4
Stratasys	Israel	Makerbot Cupcake, MakerBot Replicator
Ultimaker	Netherlands	Ultimaker 2
XYZprinting	Taiwan	Da Vinci

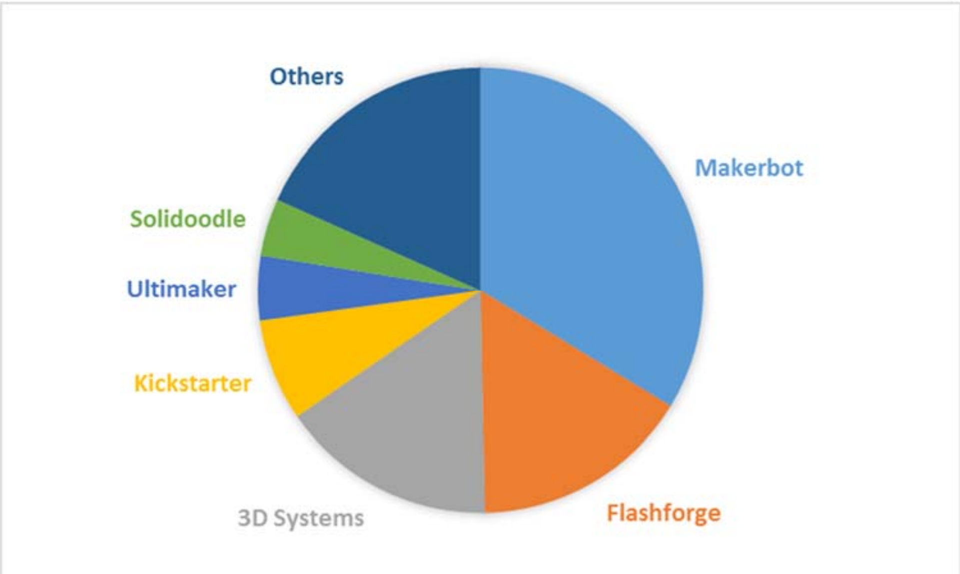

Figure 2: Marketshare consumer manufacturers.
Source: Bashir (2014)

Much of the technological progress for 3D consumer printers has been driven by the RepRap project (Budmen and Rotolo, 2013) and the Fab@Home project (Barnatt, 2013). The RepRap stands for

Replicating Rapid Prototyper. The RepRap project was started in 2005 by Adrian Bowyer from the University of Bath, with the goal of creating a machine that can replicate most or all of its own components. It is focused on fused filament technology (essentially FDM) and the RepRap project has produced a number of important machine designs that serve as milestones in the evolution of 3D printing (Budmen and Rotolo, 2013). Some of these 3D printers were eventually introduced to the market such as the Cube, Printrbot, and the RePlex3D. The Fab@Home project was started in 2006 by Hod Lipson and Evan Malone at Cornell University. The goal was to facilitate the democratization of innovating by giving each household the ability to physically create their ideas (Barnatt, 2013).

Comparing and testing 3D consumer printers is a bit complex because the industry is still in flux. For example, *Make Magazine* provided a test of 3D consumer printers, that is, the Ultimate Guide to 3D Printing 2014, a supplement to the Make Magazine in 2013. The test was conducted by leaders of 3D printer build groups and the printers were tested through printing of several products with different characteristics but the overall testing approach was a bit vague and subjective. This was followed later in November 2014 with another test, that is, the Annual Guide to 3D Printing. By that time the evaluation criteria were becoming more standardized and included seven components: dimensional accuracy test, overhang test, bridging test, positive fine feature test, tolerance test, XY resonance test, and Z resonance test. Some results were also placed online although they differed somewhat from the magazine version (www.makershed.com/pages/3d-printer-comparison). The main characteristics for 3D consumer printers are described in table 1 and include the build volume, the print speed and the print accuracy. As can be seen from table 2, the printers are still on the expensive side and typically allow only manufacturing of small products. Also, there is quite a bit of variety and some of these printers are sold in kit-form instead of fully assembled. Key items such as whether it comes with a heated build platform or not may also differ. Furthermore, it should be kept in mind that not all available 3D consumer printers were included nor all companies that produce these types of 3D printers. For example Budmen and Rotolo (2013), Barnatt (2013) and Lipson and Kurman (2013) provide information on additional companies and their products. Nevertheless, table 2 provides some insight into the current state of the 3D consumer printer industry and the main products that are available in the market.For convenience the quick styles have been set up in this template, however, a summary of the styles used is available in the table below.

Table 2: Consumer 3D printer comparison

Source: www.makershed.com/pages/3d-printer-comparison

Company-Printer	Build volume (inches)	Print speed (mm/sec)	Print accuracy (mm)	Price (US $)
Afinia H-Series	5.5x5.5x5.3	3-30	0.4-0.15	1299
Cube	5.5x5.5x5.5	15	0.2	1299
Felix	10x8x9	10-200	0.05	1749
LulzBot TAZ4	11.7x10.8x9.8	200	0.075	2194
MakerBot Replicator 2X	11.2x6x6.1	80-100	0.34-0.1	2799
MakerBot Replicator 5th gen.	9.9x7.8x5.9	Not available	0.1	2899
Orion Delta	5x5x9	40-300	0.05	1499
Printrbot Simple	3.9x3.9x3.9	70	0.1	349

Company-Printer	Build volume (inches)	Print speed (mm/sec)	Print accuracy (mm)	Price (US $)
Printrbot Simple Metal	6x6x6	Not available	0.1	599
Ultimaker 2	9x8.85x8	30-300	0.02	2499
Ultimaker Original+	8.25x8.25x8	30-300	0.02	1599

Industrial market

In contrast to the 3D consumer printer segment, there are fewer companies operating in the industrial market. In 2013, there were 34 manufacturers around the world that produced and sold professional-grade, industrial additive manufacturing systems (Wohlers Associates, 2013). In 2013, while growing by 26.4% compared to 2012, an estimated 9832 machines were sold for an average price of $90,370, while the cumulative figure is 66702 units (Wohlers Associates, 2014). As figure 3 illustrates, the two main companies are US-based 3D Systems and Stratasys (Brooke, 2013).

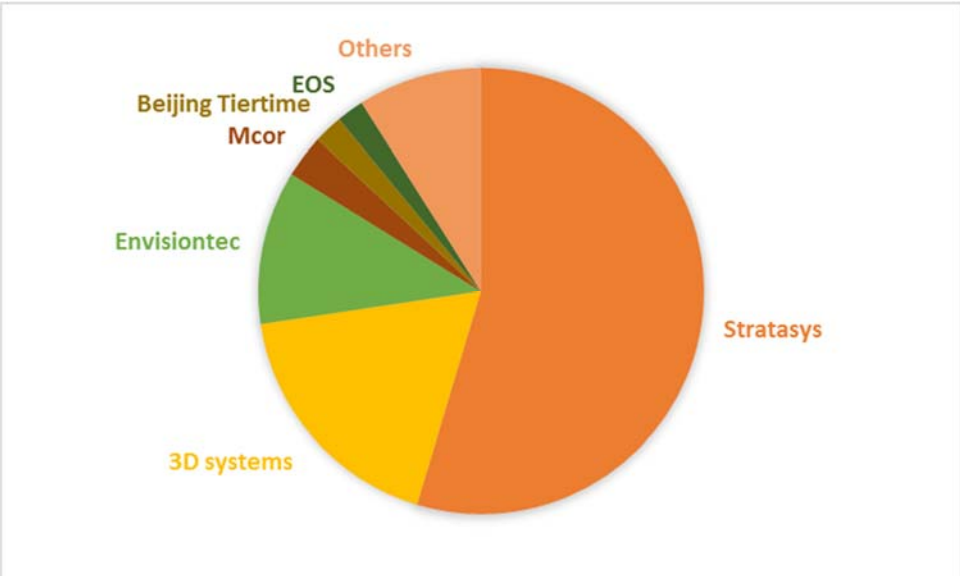

Figure 3: Marketshare industrial manufacturers.
Source: based on Wohlers Associates (2014)

Stratasys

Scott Crump was the inventor of fused deposition modelling for which he received a patent in 1988, which is also the year that he formed Stratasys with his wife (Barnatt, 2013). Stratasys has grown in part via acquisitions. For example, it took over Solidscape in 2010 and merged with another important Israeli company, Objet, in 2013. In 2013 Stratasys also merged with personal 3D printer company Makerbot, see previous section. Table 3 provides an overview of the financial growth of the company. Stratasys offers a range of products for individuals (Idea Series desktop printers), prototyping (Design Series in several classes such as Objet24, Object Connex, Objet260 Connex2, and Dimension Elite) and production (Production Series such as Fortus 900mc, Connex3 and Objet1000). Stratasys also offers machines that are specifically aimed at the dental industry. It is estimated that Stratasys has sold over 35,000 industrial systems worldwide (Wohlers Associates, 2014). As a comparison with the consumer 3D printers, the Stratasys' Fortus 900mc has a build volume of 36x24x36 inch and accuracy of better than 0.09mm and works with multiple materials.

Table 3: Stratasys financial development over time (in US$ million), Source: company website

	2007	2008	2009	2010	2011	2012	2013
Revenue	112.2	124.5	98.4	117.1	155.9	215.2	484.4
Gross profit	59.7	66.4	46.4	56.1	82.4	109.9	226.2
Net income	14.3	13.6	4.1	9.4	20.6	8.8	(26.9)

3D Systems

Charles Hull was the inventor of stereolithography for which he received a patent in 1986 which is also the year that he formed 3D Systems Corporation (Barnatt, 2013). 3D Systems has followed an aggressive growth through acquisition strategy. For instance, between early 2011 and October 2012 it acquired sixteen companies (Pfeifle, 2012). Examples are Z Corporation, Quickparts.com, Bespoke Innovations and Bits from Bytes. 3D Systems offers a range of products for personal use (ProJet 1200, Cube®3 and CubePro®), for prototyping (e.g. ProJet3510 SD, ProJet 7000 HD), for small detail-rich parts such as for jewelry (e.g. ProJet 1200), full color printers (e.g. ProJet 4500), printers aimed at healthcare and dental applcations (e.g. ProJet 6000 MP, ProX 100 Dental), and metal printers (e.g. ProX). It also operates on the consumer market for example through the Cube (see previous section). Table 4 provides an overview of the financial growth of the company. It is estimated that 3D Systems has sold almost 16,000 industrial systems. As a comparison with the consumer 3D printers, the 3D Systems' iPro 8000 (SLA) has a build volume of 25.6x29.5x21.65 inches), print speed of 25m/sec, and print accuracy of 0.05mm.

Table 4: 3D Systems financial development over time (in US$ million), Source: company website

	2007	2008	2009	2010	2011	2012	2013
Revenue	156.5	138.9	112.8	159.9	230.4	353.6	513.4
Gross profit	63.5	56.0	49.7	74.0	109.3	181.2	267.6
Net income	(6.7)	(6.2)	1.1	19.6	41.0	38.9	44.2

MARKET DEVELOPMENT

The previous sections alluded to some case study data for industrial and consumer markets in 3D printing; for example the Orion Delta in the consumer market and 3D Systems in the industrial market. It has for example been implied that there are fewer companies operating in the industrial market and that the consumer market for the 3D printing technology is in the early turbulent stages of development. The third research question, which will be addressed in this section of the paper, relates to how the market for 3D printing is developing and specifically whether there is a difference in the consumer as opposed to the industrial market development for the technology.

Figure 4, illustrates for the industrial market the number of units sold for the last few decades. It is expected that the annual sales of industrial systems in 2015 will exceed 15,000 units and that the industry will exceed $21 billion by 2020 (Wohlers Associates, 2014). However, it is not clear how this relates to consumer 3D printers because for example many personal 3D printers are non-traditional and difficult to track and (Wohlers Associates, 2014).

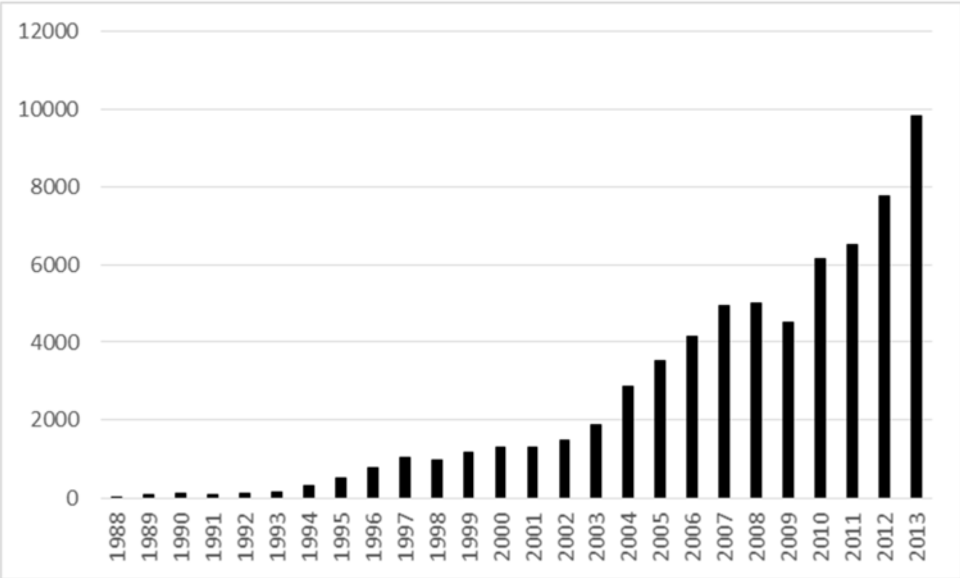

Figure 4: Industrial machines sold by year. Source Wohler Associates (2014)

The growth and development will be explored using Bibliometrics. This technique has been illustrated to be useful by Bae et al (2007). They describe it to be basically a process of measuring text and information. In this research the text and information measured is about the 3D Printing technology. As technology can also be considered to be a body of knowledge under certain circumstance the current research attempt is then about measuring the body of knowledge known as 3D Printing. Bibliometrics may also be utilized to attempt technology forecasts such as for the current case of 3DPrinting.

In the Bibliometrics approach taken here, the number of citations found in literature between a range of years is assumed to be a proxy for the cumulative growth of the 3D Printing technology or equivalently the cumulative number of technology units produced. This is useful as an initial exploratory research approach to gage the trend of the 3D Printing technology market development. In this approach the bibliometrics data on “3D Printing” and “Consumer” or “Industrial” market has been sourced in the Google Scholar data bases for the years between 1984 and 2013. One citation to 3D Printing has been found in 1984 and this concurs with evidence shown in the previous sections where it has been indicated that additive manufacturing, or 3D printing as a process were founded by Charles Hull in 1984.

The results gained from the Bibliometrics search using the Google Scholar data base have been analyzed and cumulative trends of the 3D Printing growth associated with “industrial” as well as “consumer” market are shown in figures 5 and 6. First, it can be seen that the 3D Printing technology cumulative trends seem to be different for the “industrial” and “consumer” applications. For example it should be evident from figure 5 that the cumulative “industrial” trend is 2800 units as opposed to 600 units for the “consumer” trend at year 2010. This may in some sense seem counter to the implication in the previous section where it has been stated that there are fewer companies operating in the industrial market compared to the consumer market for 3D Printing. One should however remember that this bibliometrics analysis could imply that there may have been more activities associated with “industrial” markets and development for 3D Printing technology than for the ensuing “consumer” markets during the same times of development. What is important though for the current research and related third research question is that the Bibliometrics analysis of 3D printing data for the years 1984 suggests that there is a difference in market development for "industrial" and "consumer" applications of the technology.

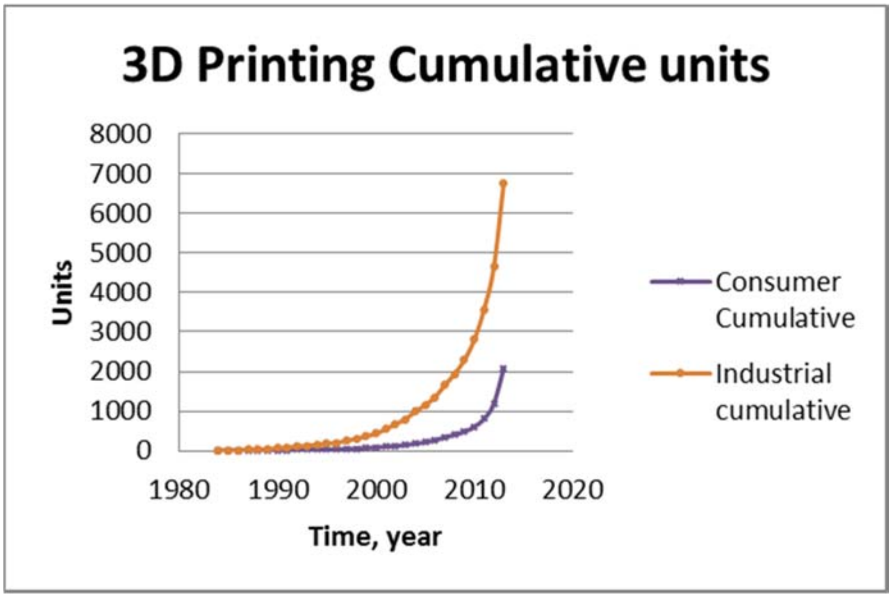

Figure 5: Bibliometric results for 3D Printing technology diffusion in cumulative units

Furthermore by comparing the rates of market penetration in units/year for "industrial" and "consumer" penetration of 3D Printing technology for the years from 2002 to 2013 as a ratio of "consumer":"industrial" it can be seen from figure 6 that the ratio has been increasing from 0.12 to 0.42 from year 2002 to year 2013. This seems to suggest that 3D Printing in the "consumer" market has been increasing in importance recently. This is in concurrence with limited performance metric for s10 companies in the consumer 3D Printing context presented in the previous sections.

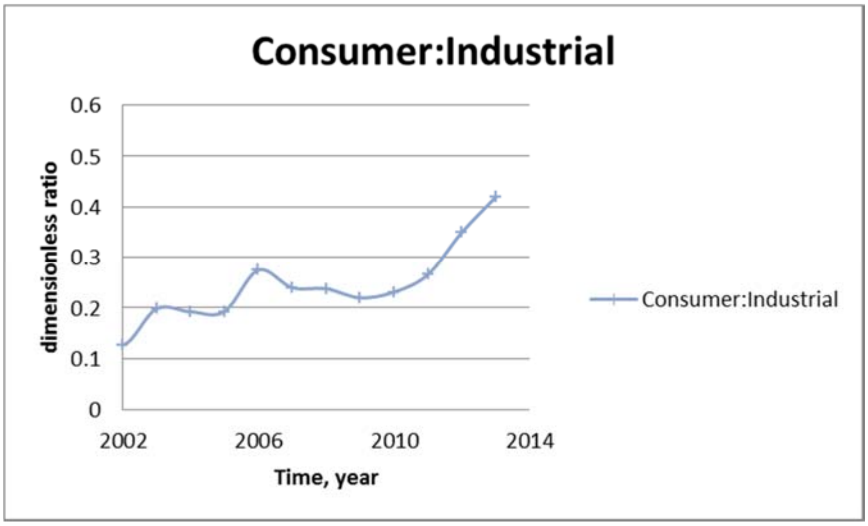

Figure 6: Bibliometric results for ratio of consumer to industrial diffusion for 3D Printing

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CONCLUSION AND FURTHER RESEARCH

The evidence produced in this research to address research question 1 on methods for 3D Printing seemed to indicate four relatively different methods for 3D Printing technology; for example currently fourth technique involves the laminated object manufacture (LOM) method that "builds objects in layers by sticking together laser-cut sheets of paper, plastic or metal foil." This research evidence supported the quite technical and advanced nature of 3D Printing as an additive manufacturing approach.

Some initial company evidence gathered to address the second research questioned pointed to a difference in industrial and consumer approach to 3D printing. This was evidenced in some basic current 3D Printing data gathered for two industrial and approximately ten consumer application companies in existence.

This also led the authors to gather Bibliometric data to in some sense address the development of the 3D Printing technology market for "industrial" and "consumer" applications. A distinct difference in the market growth patterns for these two sub technologies of 3D Printing was noted. Specifically it is concluded that for 3D Printing technology during the years 2002 to 2013 the ratio of "consumer":"industrial" penetration rate has been increasing from 0.12 to 0.42 from year 2002 to year 2013 pointing to a possible increased focus on consumer applications for 3D Printing technology as well.

Further research may include the identification and analysis of additional case studies in the areas of industrial and consumer application of 3D Printing technology. Furthermore additional data bases such as patent sources may be used to enhance the current Bibliometric analysis of 3D Printing technology. System dynamics modeling may also be used to enhance the 3D Printing market development analysis and possible technology trend forecasting.

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