Supplementary Appendix: The History of the 3D Printing Industry

The advent of 3D printing can be traced back to a Frenchmen in Paris in 1859 named François Willème who created photo sculptures of real people using similar techniques of that to the techniques used by 3D printing in today's world (Norman, 2016: Walters and Thirkell, 2007). In 1892 J.E. Blanther, a manufacturer of contour relief maps, proposed a layering method to make a mold for topographical relief maps. The method involved impressing topographical contour lines on a number of wax plates that were stacked, cut and smoothed to form a three-dimensional surface that created a raised relief map. In 1972, Matsubara of Mitsubishi Motors suggested a topographical process that used photo-hardening materials to produce layered parts (Bourell et al, 2009). Until the late 1970s the alternative primary manufacturing idea - adding material – had received comparatively little attention (except in the electronics industry for chip manufacture, where it was, and still is, ubiquitous, if microscopic). According to Bradshaw et al (2010) the advent of 3D printing started with a joke written in 1974 and a patent granted in 1977. David Jones a writer by the pen name 'Daedalus' described 3D printing as joke in the New Scientist. He gave a descriptive yet imaginative technique that proposed creation of solid objects. Coincidently, in 1977 Wyn Kelly Swainson was granted a patent for the similar idea. However, the patent was filed way before Jones piece was published.

It wasn't until 1981 that Hideo Kodama of Nagoya Municipal Industrial Research Institute published the first account of a functional photopolymer rapid prototyping system (Kodama, 1981: Bourell et al, 2009: AV plastics). The late 1980s though marked the earliest 3D printing technologies they were more known as Rapid Prototyping (RP) technologies. These processes were considered originally to be fast and most cost effective methods to create prototypes for product development within an industry (3Dprinting, 2014). Bourell et al (2009) referred this technology as additive manufacturing (AM) where the late 1980s and early 1990s saw a number of AM processes to emerge. On March 9th, 1983 an inventor known as Charles Hull used a computer controlled UV laser to trace out and solidify a single layer of an object on the surface of a tank of liquid photopolymer. Using this process he was able to create a small blue plastic tea cup. Hull had

thus invented 3D printing. On March 11th 1986 Hull managed to get the US patent for his Apparatus for production of Three dimensional Objects by Stereolithography. He also co-founded the company 3D systems Corporation where he along with his team also created the STL file format that makes CAD software data to be used for 3D printers. 3D Systems also sold its first commercial 3D printer or Stereolithography Apparatus, SLA-250 in 1988 (Barnett, 2014).

While 3D system was the pioneer of the 3D printing industry introducing SLA, at the same time during the 1980s Carl Deckard, while being an undergraduate and later a graduate student at the University of Texas, Austin, invented and developed selective laser sintering (SLS) (Lorincz, 2011). Along with his partners Deckard started a startup with the name DTM and filed for a patent in 1989 for its SLS which was later acquired by 3D Systems. In 1989 Stratasys Inc. co-founded by Scott Crump filed for a patent for Fused Deposition Modelling (FDM) which was issued in 1992 (3D printing, 2014). Stratasys alongside 3D systems was another corporate giant in the printing world. Crump discovered this invention while he was using hot glue gun to build layers of a toy frog for his daughter. By 1992 Stratasys introduced its first 3D printer "3D Modeler" (Barnett, 2014). In 1993 Royden C. Sanders the owner of Sanders Prototype later known as Solidscape built a PC-based 3D wax printer and in 1994 the first product the Model Maker was launched that created high resolution 3D wax objects. It was later acquired by Stratasys. Another company established in 1989 was a German establishment known as EOS (Electro Optical Systems). EOS introduced a machine known as EOSINT which was based on laser-sintering technology in 1994 (Wohler and Gornet, 2014). Other 3D printing technologies and processes were also emerging during these years, namely Ballistic Particle Manufacturing (BPM) originally patented by William Masters, Laminated Object Manufacturing (LOM) originally patented by Michael Feygin, Solid Ground Curing (SGC) originally patented by Itzchak Pomerantz et al and 'three dimensional printing' (3DP) originally patented by Emanuel Sachs et al. And so the early nineties witnessed a growing number of competing companies in the RP market but only three of the originals remain today — 3D Systems, EOS and Stratasys.

In terms of commercial operations, Sanders Prototype (later Solidscape) and ZCorporation (acquired later by 3D Systems) were set up in 1996, Arcam was established in 1997, Objet Geometries (acquired by Stratasys) launched in 1998 (3D printing, 2014). Arcam was a Swedish company a pioneer in the 3D printing world as well. Like 3D Systems and Stratasys, Arcam was also born out of a unique invention which used a powder bed fusion process known as Electron Beam Melting (EBM). It launched its first 3D printer the EBM S12 in 2002 (Barnatt, 2014). The sector started to show signs of distinct diversification with two specific areas during the mid-nineties. One was geared towards high end of expensive 3D printing systems that included high value production and highly engineered complex parts. The other area focused on 3D printing manufacturers who were developing and advancing "concept modellers", as known during that time. They concentrated specifically on improving concept development and functional prototyping that were being created as office and user friendly, cost effective systems. Which in today's world are said to be desktop machines. However, even then these systems were mostly used for industrial applications (3D printing, 2014). There was a major breakthrough in 1999 when scientists at the Wake Forest Institute for Regenerative Medicine invented the first lab-grown organ. The 3D technology allowed them to create a bladder with the patient's own cells. This technology opened new techniques that allowed scientists to develop strategies to engineer and print various organs (T.Rowe Price, 2012). Early 3D printing industry was dominated mostly by engineers who were the only people who used computer aided design (CAD) software to create 3D printed objects. The first two and a half decades of 3D printing was seen more like a specialized tool in a highly specialized profession (Emmino, 2012). It wasn't until the late 90's that scientist's started using 3D printing as a tool for organ development.

In 2000 Object Geometries launched the first ever 3D inkjet printer followed by Zcorp introducing the first multicolor 3D printer. In 2001 Solidimension introduced the first desktop printer (Wiljk and Wiljk, 2015). In 2002 scientists from the Wake Forest Institute for Regenerative Medicine were able to create a miniature functional kidney that was able to not only filter blood but produce urine as well in an animal (T.Rowe Price, 2012: Wiljk and Wiljk, 2015). According to Heater (2014) though the first wave of 3D printers were

developed by American entrepreneurs who were highly inventive in their garages, similar to Apple and HP, but the advent of modern desktop 3D printers surprisingly emerges from an open source project that was launched by a British University. The mission of this project was simple yet it seemed impossible and that was to create a machine that had the ability to replicate itself. Through a grant given to the University of Bath in the UK, Adrian Bowyer, a senior Lecturer in mechanical engineering at that time, started working on a technology that would have the ability to replicate itself. On 2nd February 2004 RepRap (Replication Rapid-Prototyper Project) was invented with the goal to create a self-replicating device which could be used by individuals all over the world at low cost and the ability to manufacture objects that could be used in everyday life (all3dp, 2016). It could be said that RepRap was basically the start of a new open source movement that would allowed individuals from all walks of life to use a technology that would enable them to create products on their own. RepRap was able to see the true colors of its success in the following year when the first replaceable part was printed by an early prototype. In 2008 the RepRap 1.0 Darwin successfully printed out half of its own rapid prototyped components (Heater, 2014).

RepRap was joined by Zach Hoeken in 2007 as one of the founding members with the determination of pursuing the open source movement and making all designs of his invention out in public domain (Soni, 2013). Hoeken was introduced to the concept of Open Source Hardware (OSHW) a growing trend in manufacturing where designers give access to the files that are required to replicate an object the moment it is one sale. By doing this it gives customers and supporters to not only build upon the product but also in some instances have the opportunity to gain crowd-sourced support. Smith discovered the potential OSHW had to bring a revolution in manufacturing and since then he has been releasing his work on the web in some form for others to build upon (Eagleapex, 2012). During the same period Smith met with Bre Pettis in NYC while playing Frisbees with a tech community of 20 people (Welch, 2014). Later joined by Adam Meyer together they created a small Brooklyn hackerspace known as NYC Resistor. Smith became a part of NYC Resistor and the trio worked together to create a RepRap robot that was assigned the task of generating shot glasses for robot cocktail festival held in Austria (Heater, 2014). In 2008 Thingiverse, an

online repository for 3D design files was created which allowed users to access and contribute to digital designs around the world. The three founders were still trying to create a fully functional printer that worked and hence in January 2009 they locked themselves in their hacker space where while surviving on two cases of ramen and lots of coffee they were able to create MakerBot their first product. They launched the product at South by Southwest by setting up MakerBot at bars in Austin and printing out shot glasses. After South by Southwest MakerBot had roughly about 20 MakerBot Cupcake 3D Printer kits ready to be sold. The product was an instant access and was sold out almost in a few days (Welch, 2014). Hence, giving way for the founding of a new open source company MakerBot which was later acquired by Stratasys in June 2013 (Barnatt, 2014). According to Marco and Frédéric (2014) in 2007 an idea was generated within the design department of the company Philips to build a 3D printing marketplace and community which was then further developed within the Lifestyle Incubator of Royal Philips Electronics. Hence, Shapeways was started as a spin-off of Philips in Netherlands by the founders Peter Weijmarshausen, Robert Schouwenburg, and Marleen Vogelaar. In 2011 the company relocated to the US with its headquarters located in New York (Barnatt, 2014).

While 3D printing was growing as a community supporting the idea of open source movement on the other hand there were still some major breakthrough occurring in various other fields. In 2008 it was claimed that there was a major innovations in the field of prosthetics which allowed the first person to walk on a 3D printed prosthetic legs. In 2010 Bespoke Innovations was founded by industrial designer Scott Summit and Kennith Trauner an orthopedic surgeon. “Their attention was to use 3D printing not only to return lost contour to amputees, but in addition to allow a level of personality and expression to enter the design of a truly custom prosthetic” (Barnatt, 2014, p. 138). Bio-printing also came forward as a frontier in implementing 3D printing techniques to create human tissues. Bio-printing can be traced back to a Japanese pediatrician known as Makoto Nakamura who was trying to investigate the possibility of creating mechanical inorganic prosthetics. During April 2005 and March 2008 after many failed attempts Nakamura was able to build an experimental bio-printer along with his team members. The first international

Workshop on Bio-printing and Biopatterning was held in 2004 at the University of Manchestar in UK in hoped of building a community of physicists, biologists and physicians to extend the boundaries of tissue engineering . In 2010 the first bio-printed human vessel was created by Organovo a company founded by Forgacs in 2007. This was created with the help of NovoGen MMX, the first commercial bio-printer, manufactured in partnership with Invetech. In 2012 it was announced by Organovo to be working on an Autodesk to create the first 3D design software for bio-printing so as to allow open access to multiple users (Barnatt, 2014). 2011 was also a period during which alternative 3D printing processes were being recognized at the entry level of the market. It was a time where the industrial level faced significant advances with regards to capabilities and applications, a surge in awareness and uptake across a growing maker movement and not to forget the 3D printing technology was picked up by many different mainstream media channels as well (3D printing industry, 2014).

In 2011 a group of engineers in the University of Southampton, UK built and flew the world's first 3D printed aircraft. The project was led under the supervision of Professors Andy Keane and Jim Scanlan from the University's Computational Engineering and Design Research group (eureka alert, 2011). During the same time "Urbee" the first 3D printed car was created by Jim Kor owner of Ko EcoLogic. The first model of Urbee took 2,500 hours to 3D print while the second car was printed in just six days during the International Manufacturing Technology Show held in Chicago on September 2014. Seemingly there was a rise in direct digital manufacturing (DDM) that is 3D printing of final products or as referred to by the Society of Manufacturing Engineers " the process of going directly from an electronic digital representation of a pat to the final product via additive manufacturing" (Barnatt, 2014, p.114-115). Apart from 3D printed vehicles, jewellery artists also delved into the world of 3D printing where i.materialize became the first 3D printing service worldwide that offered jewellery designers the opportunity to create jewellery using 14K gold and sterling silver materials (T.Rowe Price, 2012). 2011 onwards saw the emergence of 3D printed designer goods such as Freedom of Creation (FOC) founded by Janne Kyttanen in 2000 and later acquired

by 3D systems, 3D printed toys such as Makielab founded by Alice Taylor and Jo Roach, 3D printed Surgical Models, 3D printed Prosthesis as well as 3D printed industrial parts.

3D printing got the most public attention when the first 3D printed gun was created by Cody Wilson from Defence Distribution in 2012. Wilson made the blueprints of the gun available online however, the United State government ordered the removal of the digital files in 2013. All in all 2012 was certainly the first year for the 3D printing industry that had started to gather attention from mainstream media and public's imagination. 3D systems launched the first real consumer 3D printer– The Cube at the consumer electronics show in Los Angeles where anyone could afford the out of the box 3D printing within the price range of $1,199 also including a USB consisting of 25 ready to printout objects (Barnatt, 2013). Also a unique research project at the University of Exeter by Dr Liang Hao led to the creation of a 3D printer that created Chocolate. Hence, Choc Creator V1 became the first commercial 3D chocolate printer followed by the Choc Creator V2 and V2.0 Plus in 2014 (3ders, 2014). Coming back to Makerbot and the open source movement, in 2012 Makerbot merged with Stratasys and announced a shifted away from the open source philosophy. There were some controversies regarding this matter as Bettis defended the decision to be able to face the competition in the 3D printing industry. On the other hand co-founder Smith was against this decision explaining that the company was started on the basis of the open source movement and nothing could deter him from backing out of this stance. Smith left or more likely in his own words was forced to leave Makerbot in April, 2012. In 2012 Autodesk, one of the 3D printing software pioneers, in response to the growing demand for 3D modelling applications used by everyone launched a range of free consumer apps under the banner of Autodesk 123D. In May 2014 the company announced the launch of a new open source 3D printing software platform called Spark which was a surprise for the 3D printing community (Barnatt, 2014). Autodesk wanted to build a platform for users to build upon and render 3D objects. As stated on their blogpost (Biggs, 2014):

"Spark is an open 3D printing platform that will make it easier for hardware manufacturers, software developers, materials scientists, product designers, and more to participate in and benefit from this

technology. Spark connects digital information to 3D printers in a new and streamlined way, making it easier to visualize prints and optimize them without trial and error, while also broadening the range of materials that can be used for printing. And because the Spark platform is open, everyone can use its building blocks to further push the limits of 3D printing and drive fresh innovation".

Barnatt (2014) referred to the download of digital objects for 3D printout as the era of Open Design. Closely followed was the rise of hackerspaces, fablabs and the Maker movement which involves private individuals using design, repair and production in their own or community hands. First, starting from hackerspace's, the concept took place in Europe in Germany where the first independent hackerspace known as C-base was created in 1995 (Cavalcanti, 2013: Lindtner et al, 2014). According to Lindtner et al (2014) the hackerspace movement was drawn and departed from the history of the so called hacker culture that emerged during the 1960s/1970s. "Its members were committed to peer production, the open sharing of knowledge, and to designing technologies that were open and modifiable by users" (p.3). The hackerspace movement is basically an expanding network that is involved in integrating the ideas of web generation into hardware. Hackerspaces can best be described as social studies where various people come together and with their creativity and the facility of having a free and open sharing of equipment's, tools, software's and hardware core build creative technical projects. Typical hackerspaces are equipped with computing tools, computer controlled laser cutters as well as 3D printers. Though in Europe the hacker space movement was well known it wasn't until the August of 2007 when a group of North American hackers came to Germany and discovered the hackerspace and got excited on bringing the similar concept to the United States. In 2007 Hackerspace.org was setup by Paul Bohm and a team of other pioneering enthusiasts to bring together the different spaces electronically and help the movement grow (Barnatt, 2014). This lead to the creation of different hackerspaces such as NYC Resistor (2007), HacDC (2007) and Noisebridge (2008). Initially these hackerspaces started with electronic circuit design/manufacturing and physical prototyping, gradually they started extending their offerings which included classes and paid member access to tools to be able to cover bills and other payments. It is of no surprise that these hackerspaces eventually lead to the creation

of some revolutionary businesses such as the creation of MakerBot which was born out of NYC Resistor (Cavalcanti, 2013). Hackerspace can thus be considered as an incubation of startups and functioning in the area of research and development (Lindtner et al, 2014).

Hackerspaces and Fablabs may be broadly defined as open community workshops where members can share resources and knowledge to help them turn their ideas into physical reality. Fablabs or Fabrication Laboratory was established by Dr. Neil Gershenfeld, director of the Center of Bits and Atoms, in 2003 at the Massachusetts Institute of Technology (MIT) (Barnatt, 2014). Fablabs need to provide public access to its facilities and are equipped with a set of tools including the 3D printing technology. Fablabs were also early adopters of the 3D printing technology making it easy to access and to help in its development. Like MakerBot, a successful project emerging from a hackerspace, there was another notable 3D printer project that emerged from a Fablab known as the Dutch Ultimaker. In 2010 Erik de Bruijn and Siert Wijnia created the first Ultimake at Protospace (Fablab Utretch), in retaliation to the frustration they faced when they were unable to get the Darwin design of the RepRap to work in a proper way. It was only when they introduced Ultimaker 2 that they decided to stick to open source principles like MakerBot. During the time Fab came into existence, a publisher known as O'Reilly launched the Make Magazine in which Boston's first Fablab was featured in its first issue. The maker movement started in 2006 when the first Maker Faire took place at the San Mateo Event Center which spread across the United States and extended far to the UK in 2009 and Europe and Japan in 2013 (Troxler, 2016). Following this movement, in 2006 a website instructables.com was launched by an MIT engineer Eric Wihelm with the aim of providing step by step instructions for a number of projects. This was later acquired by Autodesk in 2011. Also in that same year Tech shop was launched with the slogan "Build your dreams". TechShop is a platform that allows individual's access to various equipment's such as 3D printers, laser cutters and wood lathes free of cost. There are 10 locations across America and it is believed that many startups sprung from these workshops such as the first prototype of the mobile device Square built by Jack Dorsey (Stone, 2015). In collaborating with 3D printing and many other equipment's individuals belonging to the maker movement envision

themselves as crafters having a global connection (Kennedy and Meyer, 2015). Looking back at RepRap and Makerbot printers they were created from a community that consisted of researchers, hobbyists, and hackers that were motivated with the ideals of the open source and maker movement. According to Barnatt (2014, p.169) “unlike a hackerspace or Fablab, nobody has to join the Maker Movement. Rather, via their actions they may simply be identified as a ‘maker’ and a part of it. All active members if hackerspaces and Fablabs ¬¬¬--- and indeed other 'makerspaces' --- are likely to be ‘makers’, as more people who currently own a personal 3D printer”. However, not everyone owns a 3D printer and in August 2013 a global web service known as 3D Hubs was launched in Amsterdam that overcame this problem and allowed individuals to use 3D Printers which was within their location.

2015 was the year of major developments in the 3D printing sector such as medical advancement with regards to facial surgery, advances in metal 3D printing, 3D printed houses, Nike, Adidas and New creations creating 3D printed shoes, the joining of major corporations such as Michelin, HP, Canon, Ricoh, Toshiba, Lenovo, Autodesk and Apple and NASA launching 3D printers in space (Kira, 2015).

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