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Chapter 2

Current and Future Business Models for 3D Printing Applications

Iñigo Flores Ituarte, Siavash H. Khajavi & Mika Salmi

§2.01 Introduction

The manufacturing of goods has always been linked to societal developments. Industrialized processes of building and replicating goods have influenced social orders, often culminating in the creation of new social constructs. In the past, different methods for fabrication have served artisans' wishes to solve day-to-day needs. Today, automation and mass-production has liberated a great part of the population, creating a large, knowledge-based society and building the foundation of the welfare society. A brief historical review shows that the second industrial revolution brought the division of labour and the reduction of marginal costs into the manufacturing of goods. The third industrial revolution came with the information age and automation. While society at large has benefited from economies of scale to create a large middle class society, the dominating models in the nineteenth and early twentieth century have constructed the welfare state as we know it today. Finally, we are now in the change towards the fourth industrial revolution, in which machines and humans will be connected in cyber-physical systems (CPS) (*see* Figure 2.1).

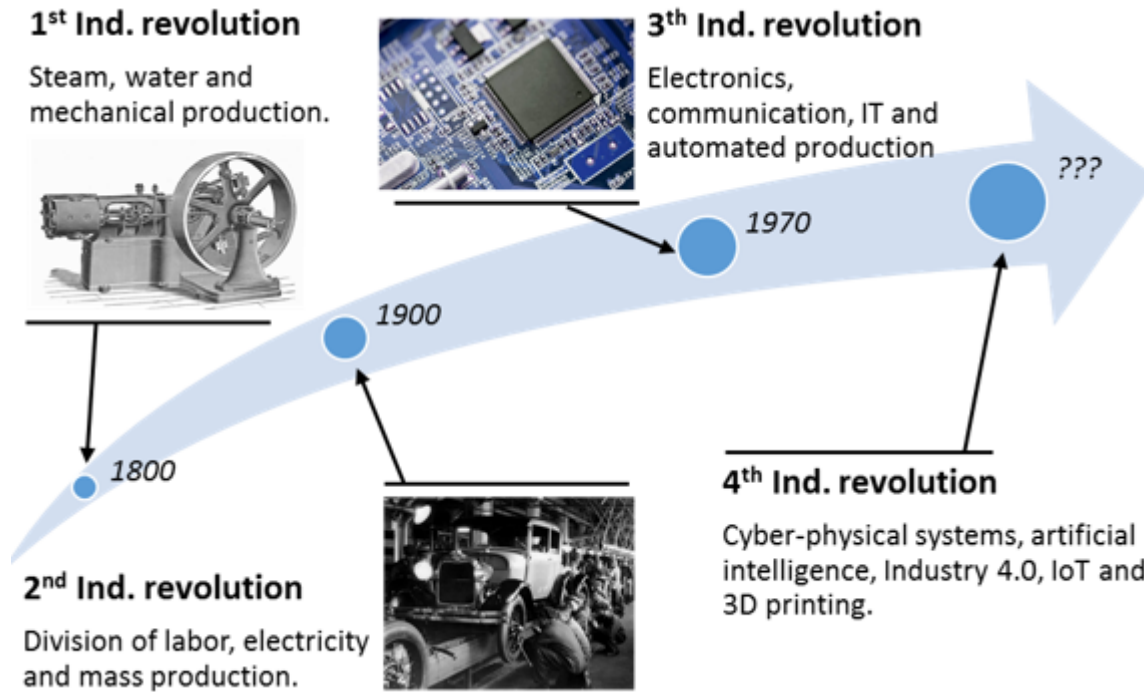


Figure 2.1: The four industrial revolutions, adapted from the World Economic Forum Global Agenda. See Klaus Schwab, *The Fourth Industrial Revolution: what it means, how to respond*, <https://www.weforum.org/agenda/2016/01/the-fourth-industrial-revolution-what-it-means-and-how-to-respond/> (published 14 January 2016, accessed 1 March 2017).

On the positive side, the fourth industrial revolution is bringing about the possibility of a new energy, communication and logistics matrix that has the potential to connect distant locations with a supply of products or services while dynamically interconnecting human activities with machines.¹ This, in turn, contributes to the movement in which consumers have become an essential part of the value creation process of firms. To some extent, 3D printing technologies combined with a new wave of internet-based communication systems are enablers of digitalization, including the digitalization of manufacturing operations and the supply chain. With this in mind, firms today have envisioned the need for more decentralized business models, shifting towards horizontals that include the consumer in the loop to create new customizable products or services and be able to serve heterogeneous niche markets. To this end, the escalating demand for personalized products and services, in combination with decreasing product lifecycles, requires further transformation of organization structures.² On the negative side, this new paradigm change is also connected to new challenges. Competition based on cost reduction is unsustainable, especially in western societies. The manufacturing share of the world's total production and the related labour force has decreased substantially in western

¹ Malte Brettel, Niklas Friederichsen, Michael Keller & Marius Rosenberg, How virtualization, decentralization and network building change the manufacturing landscape: An industry 4.0 perspective, 8 (1) *International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering* 37 (2014).

² S. Jack Hu, *Evolving paradigms of manufacturing: From mass production to mass customization and personalization*, 7 *Procedia CIRP* 3 (2013).

societies and global socio-political difficulties are challenging the solutions taken during the second and third industrial revolutions.

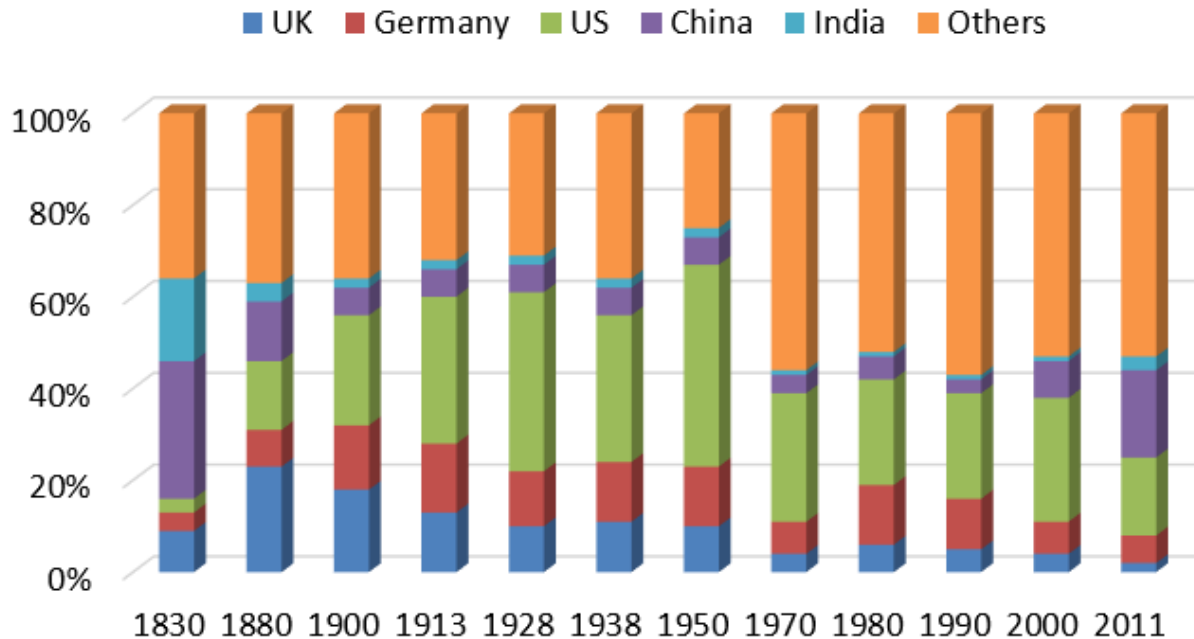


Figure 2.2: The share of major countries' manufacturing from global manufacturing monetary value adapted from Financial Times. See Peter Marsh, Caroline Nevitt, Katie Carnie & Martin Stab, *The seven ages of industry*, Financial times, <http://www.ft.com/cms/s/0/97d77036-b0c4-11e1-a2a6-00144feabdc0.html#axzz4JifPcw6w> (published 10 June 2012), accessed 1 March 2017).

In this regard, Figure 2.2 shows how, in the last 60 years, major developed economies have lost manufacturing ground (e.g. the shares of UK, Germany and US global manufacturing shrank by 8%, 7% and 27%, respectively) to the emerging economic such as China and India. Moreover, the growth of developing countries was supported by their ability to integrate second-industrial-revolution schemes into their labour market, while providing manufacturing capabilities to foreign companies in a global scale. Consequently, developed countries need to rethink their product and service delivery chains and business models. They are currently based on large, vertically integrated and centralized manufacturing operations and will need to be transformed to a network of smaller reconfigurable and interconnected production systems adjacent to demand points. However, this places tremendous pressure on existing logistics and supply chain operations.³ In addition, the lack of stability has made the market unpredictable and dynamic. In the same way, it also stresses management, leadership and decision-making roles, as industry lacks certainty for long term investments in tangible fixed assets (e.g. human resources, infrastructure and new machinery). The consumerization of manufacturing is questioning how companies need to organize their operations to have a better response to changing market needs. To this end, 3D printing technologies clearly benefit from strategies based on economies of scope and customer integration in the value chain. As a result, 3D printing technologies have come to the spotlight as a possible end-manufacturing solution. The industrialization of 3D

³ Iñigo Flores Ituarte, Siavash Khajavi & Jouni Partanen, *Challenges to implementing additive manufacturing in globalized production environments*, 5 Int. J. Collab. Enterp. 232 (2016).

printing systems is an ongoing endeavour as the transitions from ‘economies of scale to economies of one’ is becoming a reality in many industrial domains.⁴

§2.02 From Economies of Scale to Economies of One

Additive Manufacturing (AM) technologies (more colloquially known as 3D printing)⁵ represent a breakthrough in manufacturing. The technology allows the manufacturing of physical goods directly from digital data using the internet as a communication tool. With 3D printing technology, the gap between the virtual and physical world gets narrower. In the easiest possible scenario, the manufacturing operation only requires a computer-aided design (CAD) file shared on the internet to be manufactured near demand on a desktop machine. On the other end, regulated industries will require hybrid crossover solutions putting together 3D printing technologies with conventional methods of production and quality control.

In economies based on scope, traditional manufacturing methods (i.e. subtractive and formative) are more rigid, generate more waste, are less efficient for the production of complex objects in one run and require labour-intensive production systems. Additionally, they rely on economies of scale to mitigate the upfront costs of setting up a production system. Just picturing a simple scenario, you can ask to a workshop or factory today to produce a single product of your own design which is composed of several elements and materials. You will quickly realize that things are not as simple as they look. The main realization would be that in order to produce a single element in plastic, for instance, the workshop first needs to produce a mould, then cast the element in to the mould and replicate the geometry. In addition, if other parts are needed, they will need to be milled or turned and finally, after the technical requirements are met, they can be assembled and delivered to you. The problem you face is that if you require a single unit, it will become prohibitively expensive. On the other end, if you require 1,000 units of that same good, the price per part would be reduced as a function of the production volume. However, if you want to have several variations of geometry in your design to allow a certain degree of customization, the workshop will be forced to produce as many moulds as product variations. Thus, making customization and design upgrades is highly expensive.

On the contrary, the same rules do not apply to 3D printing as production costs remain basically constant and independent of production volume and the technology serves better business strategies that are based on economies of scope. In principle, this is facilitated as CAD data can be tweaked digitally and replicated in the machine with almost no impact on the production cost per part. As a result, original equipment manufacturers (OEM) are also looking at the technology as an answer to their new challenges. There is a strong body of research that presents and

⁴ Irene J. Petrick & Timothy W. Simpson, *3D Printing Disrupts Manufacturing: How Economies of One Create New Rules of Competition*, 56 (6) *Research-Technology Management* 12 (2013).

⁵ The ISO/ASTM52900–15, *Standard Terminology for Additive Manufacturing – General Principles – Terminology* defines 3D printing as the fabrication of objects through the deposition of a material using print head, nozzle or another printer technology. In a non-technical context, as in this book chapter, 3D printing is synonymously used with additive manufacturing.

summarizes the situations in which 3D printing technology provides benefits for businesses. They are as follows:⁶

- customization is an advantage (i.e., mass customization);
- innovation, design and decision-making processes need to be enhanced;
- there is a need for high geometrical complexity and low production volumes;
- products' functional performance has to be optimized (e.g. mechanical, thermal, weight reduction);
- supply chains and inventories need to become more flexible, streamlined or compressed;
- material usage needs to be reduced; and
- energy usage and waste in manufacturing has to be minimized.

Indeed, these benefits represent an opportunity for developing new business models, and, at the same time, create new challenges for existing institutions. At this point in time, the 3D printing industry has already created multiple interconnected business models. The industry is currently shaped as an ecosystem that crosses several industries, such as the medical industry, manufacturing, information and communication technologies, consumer products, consultancy, services, and retail.

§ 2.03 Unfolding the 3D Printing Ecosystem

Even though the technology dates back to the 1970s, 3D printing machines have been confined to industrial applications and were mainly used at the early stages of product development or prototyping. Just recently, the expiration of several 'core' patents on the technology, on one hand, and the creation of open-source software and self-assembly kits for 3D printers, on the other hand, have made the technology affordable and allowed it to greatly spread into consumer markets. Today, there are multiple industries adopting the technology as it shows great potential to solve many technical challenges. In addition, novel industrial strategies focused on economies of scope can be explored as the technology can solve the 'scale-scope dilemma', in which product variety can be higher without cost penalties.⁷ Firms today find great incentive in the adaptation of 3D printing technology. However, by doing so, their competitive strategies may be restrained temporarily while the learning curve is overcome.

[A] 3D Printing and Technology Applications

As mentioned earlier, traditional industrial applications of 3D printing have been connected to the early stages of the design and product development processes of firms. To some extent, the technology was mainly used in the iterative creative process of designing new products, early

⁶ Iñigo Flores Ituarte, Eero Huutilainen, Ashish Mohite, Sergei Chekurov, Mika Salmi, Jukka Helle, Meng Wang, Kirsi Kukko, Roy Björkstrand, Jukka Tuomi & Jouni Partanen, *3D printing and applications: academic research through case studies in Finland* (Nord Des. Soc. 2016).

⁷ Christian Weller, Robin Kleer & Frank T. Piller, *Economic Implications of 3D Printing: Market Structure Models in Light of Additive Manufacturing Revisited*, 164 Intern. J. Prod. Econ. 43 (2015).

stage product functionality testing and also as a tool for product designers to prototype and communicate ideas internally or externally to potential customers. The use of the technology to facilitate prototyping includes applications, such as visual aids and prototypes for fit or assembly for engineers, designers or medical professionals. In this regard, the ISO/ASTM⁸ standard defines this use as rapid prototyping (RP). In addition, 3D printing is used for tooling applications in the manufacturing sector, as it allows users to produce parts that serve as the actual tools directly (soft tooling) or tooling components indirectly, such as moulds, mould inserts, patterns for metal casting applications, patterns, silicone rubber moulds or wax models for investment casting. This process has been defined by the same ISO/ASTM standards as rapid tooling (RT). Finally, the use of 3D printing as a method to produce components to be used directly in end products or to repair or rework high value components is defined in literature as direct component manufacturing or rapid manufacturing (RM).⁹

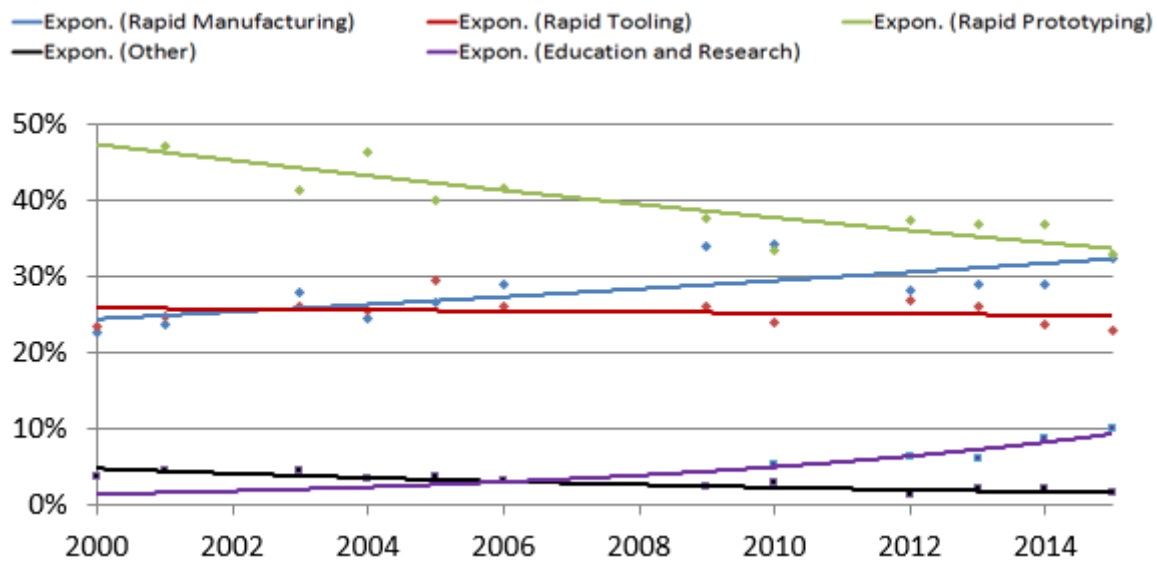


Figure 2.3: The evolution of 3D printing applications as a share in percentage. Data adapted from *Wohlers Report Additive Manufacturing and 3D Printing State of the Industry* (2000–2016).

The Wohlers report estimates that the overall 3D printing industry market, which includes all product and services worldwide, was around USD 5.2 billion in 2015.¹⁰ To have a historical perspective of the technology in terms of applications (i.e. RP, RT and RM) and its evolution in time, Figure 2.3 illustrates the percentage share of 3D printing applications during the past 15 years.

This industry had an average annual revenue growth of 26.2% during the past 27 years. In early 2000, almost 50% of the applications of 3D printing technology focused on RP, whereas RT and RM applications covered the other half. This has changed substantially over the past 15 years

⁸ ASTM, *F2792-12a - Standard Terminology for Additive Manufacturing Technologies*, ASTM International, pp.10–12 (West Conshohocken PA, 2013).

⁹ Neil Hopkinson, & Philip Dickens, *Analysis of rapid manufacturing – using layer manufacturing processes for production*, 217 (1) Proceedings of the Institute of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 31 (2003).

¹⁰ Wohlers Associates, *Wohlers Report: Additive Manufacturing and 3D Printing State of the Industry* (2016).

and nowadays the use of the technology for RP and RM are at the same level, whereas RT applications have been maintained stable covering approximately 25% of 3D printing applications. On the other end, the role of education and research in the development of 3D printing applications has become important over the last 5 years as a revenue source for the industry. This at the same time is feeding back as 3D printing systems are becoming more reliable in fulfilling the needs of high-end manufacturing applications.

[B] Industrial Drivers and Enablers of the Uptake of 3D Printing

Novel industrial applications using high-end plastic extrusion machines (i.e. material extrusion of high performances plastics, such as ABS or Ultem) and powder processing systems for metal and plastics (e.g. powder bed fusion systems to process steels, high performance metal alloys and nylon) are crossing the boundaries from prototyping towards the adoption of the technology for end use applications or RM.¹¹ The share of 3D printing technology adopters per industrial sector is presented in Figure 2.4, which illustrates the evolution of the users of 3D printing.

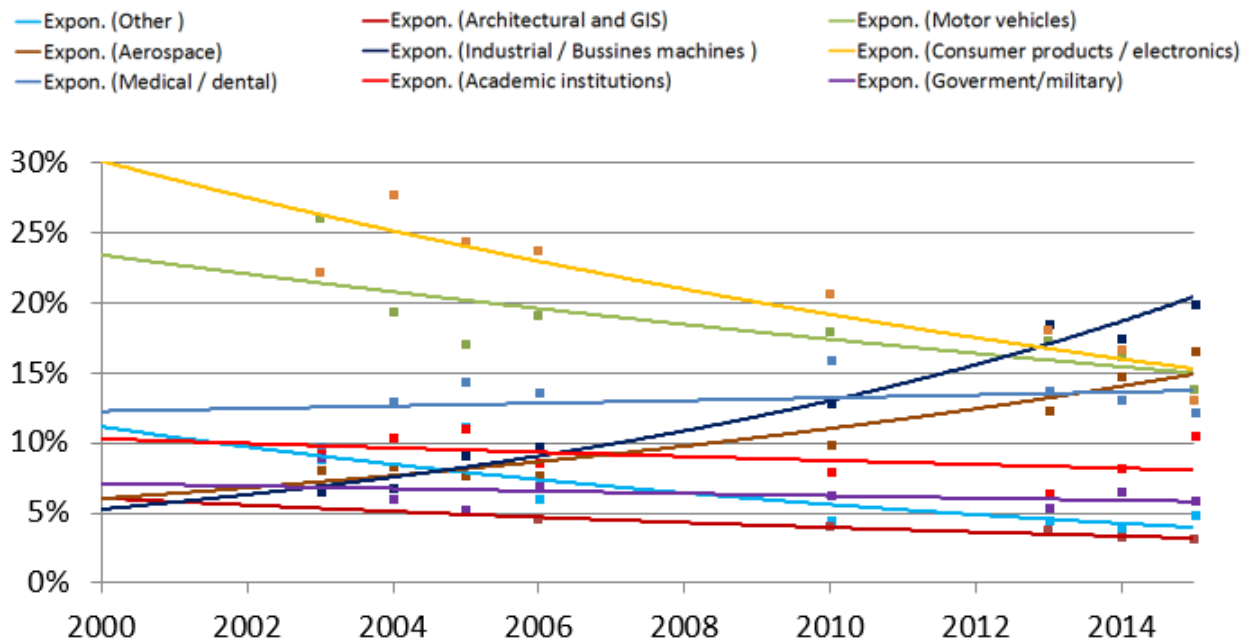


Figure 2.4: Evolution of 3D printing use per industrial sector as share in percentage. Data adapted from Wohler Reports: Additive and 3D Printing State of the Industry (from 2000 to 2016).

The pioneering applications of the technology were linked to prototyping activities for consumer product and electronics. In a similar way, the automotive industry was among the early adopters and the medical industry also used the technology to produce dentistry applications, pre-operative models and to enhance human decision making in critical medical situations.¹² On the opposite side, OEMs and the aeronautic industry started to utilize the technology later, as it

¹¹ K. Sunil, S. Tiwari, S. Pande, S. Agrawal & M. Bobade, *Selection of Selective Laser Sintering materials for different applications*, 21 (6) Rapid Prototyp. Journal 630 (2015).

¹² Jukka Tuomi, Kaija-Stiina Paloheimo, Juho Vehviläinen, Roy Björkstrand, Mika Salmi, Eero Huutilainen, Risto Kontio, Stephen Rouse, Ian Gibson & Antti A. Mäkitie, *A novel classification and online platform for planning and documentation of medical applications of additive manufacturing*, 21 Surgical Innovation 553 (2014).

gained momentum as a manufacturing solution for challenging mechanical systems. Today, the industrial drivers for 3D printing uptake are the aeronautic industry and OEMs. The major equipment manufacturers have clearly committed their research and innovation (R&I) capabilities to industrialize the technology in the coming years and use it in RM applications.

[C] Consumer 3D Printing: Innovation and Entrepreneurship

In the area of consumer 3D printing, innovations and entrepreneurial activities cover aspects such as the following:¹³

- facilitation of the design process and development of user-centred cad systems;
- online services for design, manufacturing and local distribution of 3d-printable objects;
- design, distribution, maintenance and retail of desktop 3d printing machines and materials;
- digital repositories of 3d printable models for industrial or commercial applications;
- 3d scanning technologies and reverse engineering software; and
- an active maker community and local manufacturing hubs or Fablabs.

Making prototypes or testing ideas has never been as easy and as cheap as it is now.¹⁴ To some extent, emerging companies have the ability to create a whole new market using the internet as the main tool for communication and monetization. In turn, 3D printing technologies are used to reproduce physical goods for prototyping or final products for their customers.

The academia has already pointed out education and technical skills as one of the main challenges in the uptake of 3D printing.¹⁵ There is a clear need for high level of competence and knowledge to be able to utilize the technology as well as its related digital systems.¹⁶ In this regard, education on 3D printing technologies crosses multiple disciplines and one of the most recognizable skills is the ability to generate digital designs (i.e. CAD files). Traditionally, professional profiles with this set of skills include engineers, architects and designers. To bridge the gap today, multiple user-centred CAD solutions are freely available on the internet, thus making CAD accessible to a bigger audience. Many web-based modelling tools make the process of creating digital 3D representations accessible (e.g. Tinkercad¹⁷ and Sketchup¹⁸). Looking at the basic principles of CAD, the 3D modelling process has similarities to handcraft sculpting but in a digital environment and there are also initiatives that address the need of early stage education. Startup companies are also teaching children to 3D model with their hands, reducing the learning curve on technical drawing and 3D modelling. An example of this is presented in

¹³ MIT's Center for Bits and Atoms, *Fab Lab FAQ*, <http://fab.cba.mit.edu/about/faq/> (accessed 1 March 2017).

¹⁴ Rosa Maria Ballardini, Juho Lindman & Iñigo Flores Ituarte, *Co-creation, commercialization and intellectual property – challenges with 3D printing*, 7 *Eur. J. Law Technol.* 1 (2016).

¹⁵ Royal Academy of Engineering, *Additive manufacturing: opportunities and constraints*, <http://www.raeng.org.uk/publications/reports/additive-manufacturing> (accessed 1 March 2017).

¹⁶ Christiane Beyer, *Strategic implications of current trends in additive manufacturing*, 136 (6) *J. Manuf. Sci. Eng.* 64701 (2014).

¹⁷ Tinkercad, <https://www.tinkercad.com/> (accessed 1 March 2017).

¹⁸ Sketchup, <http://www.sketchup.com/> (accessed 1 March 2017).

Figure 2.5 in which a kindergarten child has the ability to generate 3D geometries that can be replicated in a 3D printer afterwards.



Figure 2.5: A 5-year-old child using a physical CAD modelling tool courtesy of Atomicshapes, <http://www.atomicshapes.fi/> (accessed 1 March 2017).

As mentioned earlier, once a 3D model has been created it can be printed. To do so, innovative companies, such as Shapeways¹⁹ or i.materialise,²⁰ facilitate the process by providing 3D printing as an online service. In this regard, 3D printable consumer products can be designed by individual users and sold to customers all around the globe using their online platform. Moreover, if, at the customer end, there is a need to create individualized designs, the platform allow them the ability to manipulate the original model to some extend and print out personalized objects by changing geometrical and aesthetic features of the original design, thus allowing mass customization. Other visible examples of innovation and entrepreneurship are related to the design and distribution of desktop 3D printing machines and materials. To this end, some of the most visible brands are Makerbot,²¹ Ultimaker²² and XYZ Printing.²³ However, nearly every country, if not city, has its own company who has designed, built and tries to commercialize desktop machines based on material extrusion technology. The original technology in all these machines is based on expired of patents owned by Stratasys²⁴ and the trademark for this technology is fused deposition modelling. Currently their main market is

¹⁹ Shapeways, <http://www.shapeways.com> (accessed 1 March 2017).

²⁰ Imaterialise, <http://www.imaterialise.com> (accessed 1 March 2017).

²¹ Makerbot, <http://www.makerbot.com/> (accessed 1 March 2017).

²² Ultimaker, <https://ultimaker.com/> (accessed 1 March 2017).

²³ XYZprinting, <http://eu.xyzprinting.com/> (accessed 1 March 2017).

²⁴ Stratasys, *FDM Technology*, <http://www.stratasys.com/3d-printers/technologies/fdm-technology> (accessed 1 March 2017).

focused on education, schools, universities and libraries as well as home users and technology enthusiast.

Another complementary service which has grown in parallel with the consumer desktop 3D printing business are online platforms that store CAD data to download and act as design repositories. There are multiple license agreements in these platforms, but the main principle is that the platforms allow the user to access a wide range of ready-made 3D models, download them, modify them, redistribute them and ultimately print them. For instance, CAD data repositories, such as GradCad,²⁵ 3D Warehouse,²⁶ Cult3D,²⁷ PinShape,²⁸ Thingiverse,²⁹ Sculpteo³⁰ or Kazzata,³¹ can be used to download 3D printable gadgets or spare-parts to be 3D printed and utilized. Scanning technologies have reached a wider audience. Today, having a digital camera and dedicated reverse engineering software to post-process images is enough to generate a 3D printable model. A set of photographs, taken with your smartphone, can be used to generate a 3D model using an app³² or users can upload the photos to an online software, such as 123D Catch,³³ to generate 3D printable models. Semi-professional hardware and software combos, such as Sense,³⁴ Artec³⁵ and David,³⁶ are extremely affordable for the same task. In this regard, clear copyright infringements could be found in objects that have been 3D scanned by users and shared via websites. The adoption of 3D printing technologies has also fostered new geographies of production and innovation that have become more inclusive, dynamic, and horizontal (e.g. the maker movement³⁷). Cities and universities all around the globe have promoted the creation of local factories or Fablabs.³⁸ These places help local communities to collaborate and brainstorm ideas as well as develop and prototype products or services that address local needs. These initiatives are tightly connected with the local entrepreneur initiatives and in some cases they end up becoming products or services that are sold commercially.

[D] 3D Printing as a Business Ecosystem

Originally, the concept of business ecosystem was first presented in an article in the Harvard Business Review.³⁹ In this work, Moore defined the ‘business ecosystem’ as a random collection of interconnected or networked elements (i.e., suppliers, lead producers, companies, competitors

²⁵ Grabcad, <https://grabcad.com/> (accessed 1 March 2017).

²⁶ 3D Warehouse, <https://3dwarehouse.sketchup.com/?hl=en> (accessed 1 March 2017).

²⁷ Cults3d, <https://cults3d.com/> (accessed 1 March 2017).

²⁸ Pinshape, <https://pinshape.com/> (accessed 1 March 2017).

²⁹ Thingiverse, <https://www.thingiverse.com/> (accessed 1 March 2017).

³⁰ Sculpteo, <https://www.sculpteo.com/en/> (accessed 1 March 2017).

³¹ Kazzata, <http://kazzata.com/> (accessed 1 March 2017).

³² Tridimensional, <http://www.tridimensional.com/> (accessed 1 March 2017).

³³ Autodesk, *123D Catch*, <http://www.123dapp.com/catch> (accessed 1 March 2017).

³⁴ 3Dsystems, *3D Systems Delivers Sense Consumer 3D Scanner*, <http://www.3dsystems.com/press-releases/3d-systems-delivers-sense-consumer-3d-scanner> (published 8 November 2013, accessed 1 March 2017).

³⁵ Artec3d, <https://www.artec3d.com/> (accessed 1 March 2017).

³⁶ David, <http://www.david-3d.com/en/> (accessed 1 March 2017).

³⁷ Jane Wakerfield, *Makers unite - the revolution will be home-made*, <http://www.bbc.com/news/technology-19347120> (published 16 September 2012, accessed 1 March 2017).

³⁸ MIT Center for Bits and Atoms, *Fab Lab FAQ*, <http://fab.cba.mit.edu/about/faq/> (accessed 1 March 2017).

³⁹ James.F. Moore, *Predators and prey: a new ecology of competition*, 71 (3) Harv. Bus. Rev. 75 (1993).

and other stakeholders) that produces goods and services of value to customers. This work also explains that, over time, all the ecosystems gradually evolve to a more structured community, become more consolidated and tend to be aligned in the direction set by one or more key leading companies. The 3D technologies today are shaped like a networked ecosystem. Currently, however, stakeholders that generate and obtain value from the ecosystem are extremely fragmented with no clear 'one-stop shop' solution provider offering end-to-end solutions.

This may be grounded in the following points. First, 3D printing has been in the shadows for the last three decades and has just recently come to light as a disruptive technology. In the early days, the technology was not mature enough to fulfil the requirements of manufacturing applications. Second, industrial companies able to get value from the technology exist across multiple markets, such as the medical industry, manufacturing, information and communication technologies, consumer products, consultancy, services, and retail. Third, the consumer side of the business has created multiple entrepreneurial activities. As a consequence, the dichotomy between B2C and B2B activities is not clearly defined. Finally, there are multiple technical elements that merge in one single ecosystem involving design aspects, hardware, materials and software.

To a certain extent, the 3D printing ecosystem as a whole is trying to expand and conquer other markets and has become very dynamic and difficult to predict. The existing body of knowledge presents the 3D printing industry at the expansion stage – and the data also supports this hypothesis as the industry has an average revenue growth of 26.2% every year during the past 27 years.⁴⁰ If we use the analogies presented by Moore, this stage is presented as the process of bringing a new offer to a large market by scaling up operation and maximizing market coverage. The challenges are obvious – firms in the 3D printing ecosystem need to defeat alternative already existing solutions and establish power relations to other players.

Gibson described this phenomenon in 3D printing as 'technology convergence.'⁴¹ In his work, he mentions the tendency to view 3D printing as an isolated technology that has somehow taken the world by storm, which is far from the reality. 3D printing would not be of any benefit if it was not combined with other technologies, such as 3D solid modelling CAD. In addition, the technology is evolving to be used in conjunction with other manufacturing technologies to be able to serve diverse applications domains.

To this end, Figure 2.6 shows a holistic representation of the 3D printing industry ecosystems. The network analysis presented here introduces the main actors or companies, clustered firstly in four major groups and categorized in a green box (i.e. technology users and industry, machine and system vendors, software and IT platforms and manufacturing services bureaus). Secondly, the hierarchy within these four groups breaks down to other sub-groups.

These are represented by yellow bubbles and categorized by the primary industrial activities of the companies (e.g. raw materials, automotive, retail, aerospace, CAD, and simulation). The

⁴⁰ Forbes, *Wohlers Report 2016: 3D Printing Industry Surpassed \$5.1 Billion*, <http://www.forbes.com/sites/tjmccue/2016/04/25/wohlers-report-2016-3d-printer-industry-surpassed-5-1-billion/#4534d367cb14> (published 25 April 2016, accessed 1 March 2017).

⁴¹ Ian Gibson, *The changing face of additive manufacturing*, 28 (1) J. Manuf. Technol. Manag. 10 (2017).

connecting lines describe the interrelations between companies as well as between clusters. The stronger the links between clusters or companies, the thicker the lines are. In addition to clusters and companies, other elements interact with the development of AM technology towards a massive adoption. These groups are represented by orange bubbles and include services, such as consultancy, professional training, financing, policy, industry standards, qualification, certification, research and education.

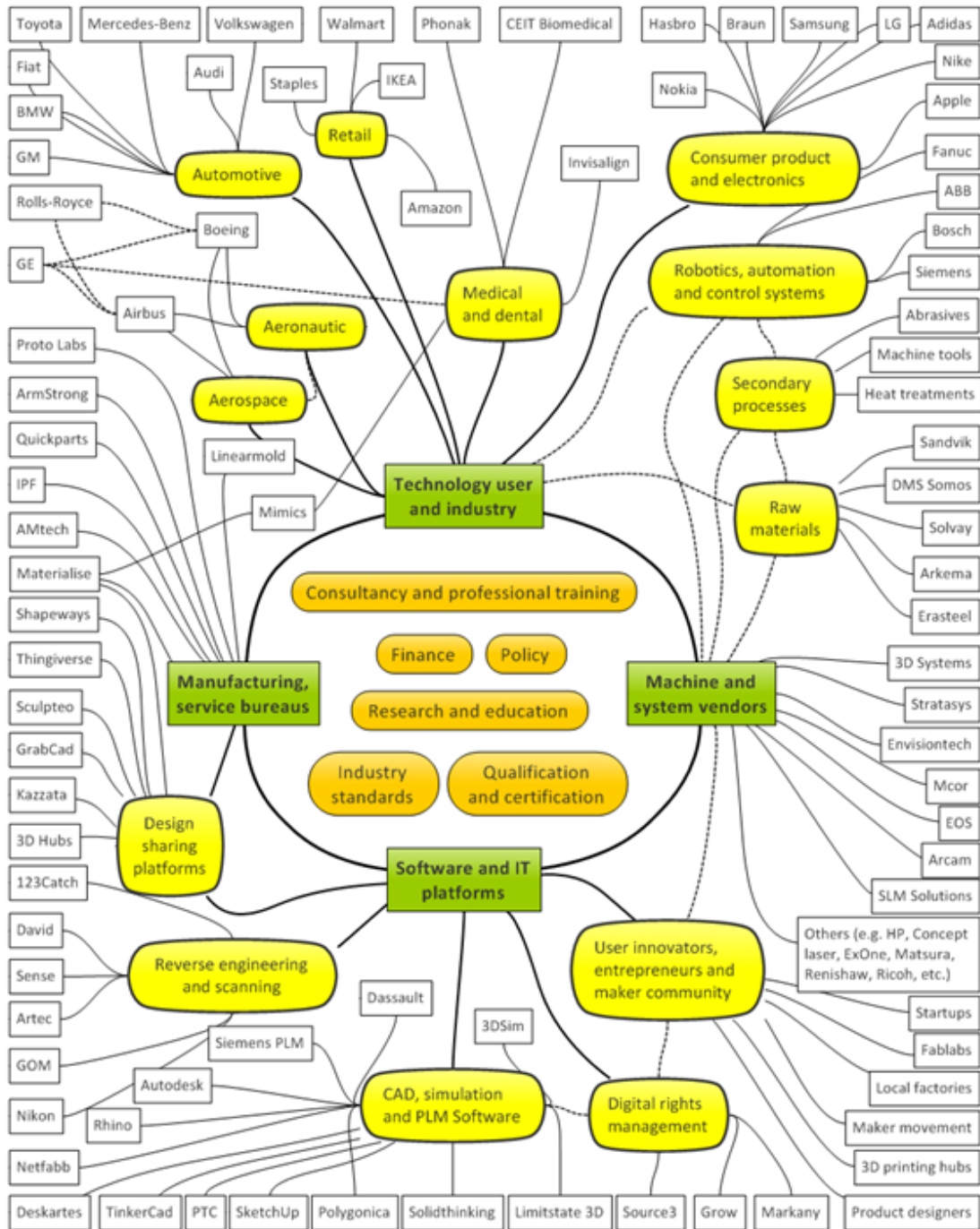


Figure 2.6: The 3D printing industry as a networked ecosystem

With all these actors in mind, what is relevant for further development of the ecosystems is that there are some clear market dominators. Some companies have already created verticals, positioning their value creation at multiple levels of the ecosystem with the ability to provide upstream and downstream value to technology users and the industry in general. The challenge to visualize the ecosystem is that the companies that provide physical and virtual goods are blended. As a consequence, it is hard not to fall for a simplification when describing the 3D printing technology ecosystem. The following chapter will go more into detail how some of the companies mentioned in the ecosystem are positioning their business models today to create value and monetize their activities.

§2.04 Business Models: How is 3D Printing Monetized Today?

[A] Machines, Materials and System Suppliers

Early stage developments in the 1990s created a set of companies operating in different areas of the 3D printing ecosystem. At that time, the focus was on the development of base machine technologies and intellectual property (IP), suitable materials to be processed and, finally, software systems to control the processes. After the early stages of maturation, these areas of development started to converge and companies today try to find business models all around the ecosystem. Currently and based on the data collected in 2015, the Wohlers report⁴² lists the biggest companies in the 3D printing business with respect to the number of machines sold as Stratasys⁴³ (5,166 units sold), 3D Systems⁴⁴ (1,925 units sold), EnvisionTEC⁴⁵ (1,250 units sold), Mcor Technologies⁴⁶ (700 units sold), EOS⁴⁷ (370 units sold), SLM solutions⁴⁸ (102 units sold) and Arcam⁴⁹ (60 units sold). However, the number of machines sold does not speak about the revenue or operating profit. In this regard, the two biggest publicly listed companies are Stratasys (with a revenue of USD 696 million in 2015) and 3D Systems (with a revenue of USD 666 million).⁵⁰ The *Wohlers Report* estimates that during 2015, USD 1.516 billion was spent on the purchase of new 3D printing systems and machine upgrades. On the other end, USD 768 million was spent on 3D printing materials during the same period.

Traditionally, the business model of machine developers was inclusive to third parties and machines had an open hardware-software architecture. This made sense as third parties could develop materials and systems to be used in the original equipment, incentivizing the industry to develop more rapidly. With this model, more companies and R&D organizations, with knowledge and expertise in materials or software, had the ability to contribute and mature the

⁴² Wohlers Associates, *Wohlers Report: Additive Manufacturing and 3D Printing State of the Industry*, *supra* n. 10.

⁴³ Stratasys Ltd., <http://www.stratasys.com/> (accessed 1 March 2017).

⁴⁴ 3D Systems Inc., <http://www.3dsystems.com/> (accessed 1 March 2017).

⁴⁵ EnvisionTEC Inc., <http://envisiontec.com/> (accessed 1 March 2017).

⁴⁶ Mcor Technologies Ltd., <http://mcor technologies.com/> (accessed 1 March 2017).

⁴⁷ EOS GmbH Electro Optical Systems, <http://www.eos.info/en> (accessed 1 March 2017).

⁴⁸ SLM Solutions Group AG, <https://slm-solutions.com/> (accessed 1 March 2017).

⁴⁹ Arcam AB, <http://www.arcam.com/> (accessed 1 March 2017).

⁵⁰ The NASDAQ Stock Market, <http://www.nasdaq.com> (accessed 1 March 2017). 3D Systems Corp. (share ticket DDD) & Stratasys Ltd. (share ticket SSYS)

technology together. However, currently, the main machine developers have taken a different approach. The systems have been locked so that the materials need to be provided and certified by the same vendor. Only in special cases, and thanks to bilateral agreements, do other parties have the possibility to develop secondary technologies (i.e. materials and software) and commercialize them in parallel. To some extent, this ‘Razor/Razorblade’ business model is suitable to drive the technology into production environments. In this context, there is a strong need for quality and control within the process.⁵¹ With this in mind, influential parameters, including materials and software, are optimized by the machine manufacturer to allow higher reliability and repeatability of the production process. Nevertheless, there are still many companies that produce and develop raw materials for the main machine vendors. Currently, there are three main raw material providers:

- DMS Somos,⁵² which is mostly focused on developing photo-curable resins for vat-photopolymerization, thermoplastic for extrusion as well as standard powders for powder bed fusion systems;
- Solvay,⁵³ which develops polyamide plastic powder for powder bed fusion; and
- Sandvik,⁵⁴ which focuses on metal powders for powder bed fusion systems.

Still, the raw material producers’ role is strong in cases where large volumes of material are needed (e.g. photopolymers for prototyping with vat-photopolymerization machines, standard filaments of ABS or PLA for material extrusion and standard metals or plastics powders for powder based processes) or the material cost is high (e.g. precious metal powders). A special case is the supply of thermoplastic filaments for extrusion systems being extremely fragmented due to the proliferation of the technology in non-professional settings. Nevertheless, it has been estimated that the materials market can overtake the 3D printer market in 2021.⁵⁵

Following the current digitalization trend, software platforms for 3D printing have become as important as the hardware itself. Therefore, in many cases, the CAD models often require different automated pre-processing and repairs before they can be 3D printed. Many companies provide software for end-users or might have partnerships with the machine vendors that require plugins to their systems (e.g. slicing algorithms, algorithms for machine motion control, automation and control systems). In this regard, there are companies who are visibly active in this area (e.g. Materialise,⁵⁶ DeskArtes⁵⁷ or Autodesk-NetFabb⁵⁸). In addition, in the process of industrializing 3D printing systems, a new set of software-hardware solutions is often required. In this regard, newcomers in the field are presenting novel solutions for quality control (e.g.

⁵¹ Iñigo Flores Ituarte, Eric Coatanea, Mika Salmi, Jukka Tuomi & Jouni Partanen, *Additive Manufacturing in Production: A Study Case Applying Technical Requirements*, 78 Physics Procedia 357 (2015).

⁵² Royal DSM, <http://www.dsm.com> (accessed 1 March 2017).

⁵³ Solvay, <http://www.solvay.com> (accessed 1 March 2017).

⁵⁴ Sandvik AB, <http://smt.sandvik.com/en/> (accessed 1 March 2017).

⁵⁵ R. Gordon & J. Harrop, *3D Printing Materials 2016-2026: Status, Opportunities, Market Forecasts Pricing, properties and projections for materials including photopolymers, thermoplastics and metal powders* (IDTechEx report 2016).

⁵⁶ Materialise NV, <http://www.materialise.com/> (accessed 1 March 2017).

⁵⁷ DeskArtes Oy, <http://www.deskartes.com/> (accessed 1 March 2017).

⁵⁸ Autodesk Inc., <https://www.netfabb.com/> (accessed 1 March 2017).

Sigma Labs⁵⁹) or software for secure distributed manufacturing and intellectual property right management (e.g. Grow Software⁶⁰ or Source3⁶¹). What is common to the software business is that solutions are easily scalable and therefore have potential for growth as the digitalization of companies evolves.

Looking only at the growth rate of machine vendors, companies today that are focused on powder systems for metal and plastic processing (e.g. EOS, SLM Solutions and Arcam AB) are growing steadily and driving the industry. Their machines have been designed for niche RM applications, such as value-added original equipment manufacturers, and the medical, aerospace and automotive industry.⁶² In the past years, big international companies have also moved into the 3D printing business. One of the most visible examples of this was Hewlett-Packard,⁶³ which has developed a proprietary technology claiming to be ten times faster than existing solutions with comparable material properties.⁶⁴ The expected launch of the new 3D printing system is planned for late 2017. Although the full capabilities remain to be discovered, looking only at the Hewlett-Packard's market capitalization of around USD 29 billion (early 2017), which is multiple times higher than the current 3D printing market leaders (market capitalization of 3D Systems and Stratasys during the same period were about USD 1.7 billion and USD 1.05 billion respectively), one should count HP as a serious contender. Moreover, it is not unlikely to see Hewlett-Packard acquiring any of these companies in the future. In this regard, if they acquired either 3D Systems or Stratasys, Hewlett-Packard would then be the indisputable leader within the 3D printing ecosystem. Putting aside speculations, other prominent companies, such as the Japanese Canon and Ricoh, have also entered the 3D printing market. In this process, Canon has developed machines in partnership with 3D Systems aiming to get to the 3D printing market faster.⁶⁵ On the other hand, Ricoh has developed a partnership with the consumer 3D printer manufacturer LeapFrog and also presented an industrial laser sintering machine.⁶⁶ Finally, on the software side, Autodesk has taken a strong position in the industry and announced Spark,⁶⁷ which is an open 3D printing platform upon which any company can build.

[B] In-house Manufacturing Capacity

From the technology user's perspective, owning machinery makes sense and is feasible when 3D printing is considered as a strategic advantage in the future of company operations. In this model, the original equipment manufacturer has in-house capabilities as well as the infrastructure to

⁵⁹ Sigma Labs Inc., <https://www.sigmalabsinc.com/> (accessed 1 March 2017).

⁶⁰ GROW Software Ltd., <https://www.grow.am/> (accessed 1 March 2017).

⁶¹ Source3, <http://source3.io/> (accessed 1 March 2017).

⁶² See Figure 2.4.

⁶³ HP Development Company L.P., <http://www8.hp.com/us/en/printers/3d-printers.html> (accessed 1 March 2017).

⁶⁴ Pete Basiliere, *HP Brings a Strong First Offering to the 3D Printing Market*, Gartner <https://www.gartner.com/doc/3320417?ref=SiteSearch&stkw=3d%20printing&fml=search&srcId=1-3478922254> (published 17 May 2016, accessed 1 March 2017).

⁶⁵ Rapid News Publications Ltd., *Canon makes 3D printing market debut with new resin-based technology*, <http://www.tctmagazine.com/3D-printing-news/canon-enters-3d-printing-market-with-new-resin-based-technology/> (accessed 1 March 2017).

⁶⁶ Ricoh Europe, <http://www.ricoh-europe.com/products/3D-printers/> (accessed 1 March 2017).

⁶⁷ Autodesk Inc., <http://spark.autodesk.com/> (accessed 1 March 2017).

supply parts using 3D printing technology. These facilities serve the needs of the organization in terms of RP, RT or RM of value-added key components. The post-processing needs to be taken into account when planning in-house manufacturing since parts might need secondary processes, such as heat treatment, machining or polishing. Industries adopting this model are aerospace and aeronautic applications. Companies such as General Electrics (GE), Boeing or Airbus have created specific development programs to establish in-house manufacturing capacity for metals and plastic components to internally drive the industrialization of the technology. As an example of this, GE has opened several advanced manufacturing centres in Pittsburgh,⁶⁸ South Carolina,⁶⁹ Italy⁷⁰ and India,⁷¹ having more than 300 machines in use across GE.⁷² Competitors have also followed the trend: Boeing already has more than 20,000 3D printed plastic parts flying in their commercial aircrafts⁷³ and internal machine capacity. Moreover, approximately 150 parts in the forward fuselage area of the F/A-18 Super Hornet have been produced through selective laser sintering.⁷⁴ The benefits for the aerospace and aeronautic industry are straightforward as improving the Buy-to-Fly ratio (i.e. reducing the weight ratio between the raw material used for a component and the weight of the component itself), especially for precious metals such as titanium, is a common objective. In addition, the weight reduction of other metal and plastic parts by optimization is technically and economically beneficial over the lifecycle of the aircraft.

The benefits of in-house capacity is not exclusive for the aerospace and space industry. There are examples from other industrial sectors, such as automotive, consumer electronics or manufacturing industry in general. For example, Siemens invested EUR 21.4 million to open a new metal 3D printing facility in Sweden to develop new improved components and repairs for turbo machinery applications.⁷⁵ The simplification of mechanical systems using part consolidation is also a fundamental factor for the adoption of the technology. For instance, Kuhn-Stoff⁷⁶ has been able to reduce the number of components of a complex mechanical

⁶⁸ Business Wire Inc., *GE Celebrates Grand Opening of First Additive Manufacturing Center in Pittsburgh*, <http://www.businesswire.com/news/home/20160405005970/en/GE-Celebrates-Grand-Opening-Additive-Manufacturing-Center> (accessed 1 March 2017).

⁶⁹ Business Wire Inc., <http://www.businesswire.com/news/home/20160422005789/en/GE-Power-Opens-Advanced-Manufacturing-Facility-400> (accessed 1 March 2017).

⁷⁰ GE newsroom, *GE Oil & Gas to use robotics and 3D printing in futuristic Talamona plant*, <http://www.genewsroom.com/press-releases/ge-oil-gas-use-robotics-and-3d-printing-futuristic-talamona-plant-282977> (accessed 1 March 2017)

⁷¹ Benedict / 3ders.org, *GE's \$200M 'Brilliant' 3D printing factory in Pune, India to develop critical end-use parts*, <http://www.3ders.org/articles/20160407-ge-200-million-multi-modal-3d-printing-factory-pune-india-develop-critical-end-use-parts.html> (accessed 1 March 2017).

⁷² General Electric, *GE Brilliant Factory*, <http://www.ge.com/stories/advanced-manufacturing> (accessed 1 March 2017).

⁷³ Brian Krassenstein, *20,000 3D Printed Parts Are Currently Used on Boeing Aircraft as Patent Filing Reveals Further Plans*, <https://3dprint.com/49489/boeing-3d-print/> (accessed 1 March 2017).

⁷⁴ 3DPrinting.com, *Boeing files patent for 3D-printed aircraft parts*, <http://3dprinting.com/news/boeing-wants-to-patent-3d-printing-of-aircraft-parts/> (accessed 1 March 2017).

⁷⁵ Rapid News Publications Ltd., *Siemens opens Sweden's first workshop for 3D printing metal components*, <http://www.tctmagazine.com/3D-printing-news/siemens-swedens-first-workshop-3d-printed-metal-components/> (accessed 1 March 2017).

⁷⁶ Kuhn-Stoff GmbH & Co KG, *About 80% weight reduction compared to conventional gripper with same holding force*, http://www.kuhn-stoff.de/fileadmin/benutzerdaten/kuhn-stoff-de/pdf/downloads/Bronchialgreifer_Diodenklemme.pdf (accessed 1 March 2017).

gripper from twenty-one to two. The new solution is economically viable since the cost is approximately half of the original and production takes a quarter of the time. In addition, the previous solution used an assembly of twenty-one different components made from materials, such as aluminium, rubber or plastic. Technical performance has also improved as the new solution is 86% lighter than the previous version. With this in mind, research and innovation activities across industries are focused on mapping 3D printable components that can be improved in terms of functionally or systems performance by reducing the amount of assembly parts and consolidating the design into primary key elements, while keeping the overall functionally intact. This, in the end, positively impacts the overall performance of the product and the cost of the system and simplifies the supply chain and inventories of the companies.⁷⁷ The other main driver for adopting in-house capabilities is the medical industry. Dental and medical applications are good examples of mass-customization since every patient's ergonomics are unique. In this regard, the most visible example of successful business models in medical mass-customization refers to hearing aid shells. Currently, companies such as Siemens,⁷⁸ Phonak⁷⁹ and Starkey⁸⁰ produce more than 10 million units of fully customized hearing aid shells using 3D printing technologies and are replacing conventional methods of production completely. Other examples are related to dental industry, in which dental labs use 3D printers to create anatomical models of teeth and gums and implants such as crowns and bridges.⁸¹ Aligners⁸², dentures, drill guides and bite splints⁸³ can benefit from 3D printing. In the medical field, anatomical models, medical aids, orthoses, splints, prostheses, donor face restorations⁸⁴ and implants⁸⁵ can be made using 3D printing and firms are currently incorporating this technology.

[C] Contract Manufacturing Model: Service Bureaus

⁷⁷ Ituarte, Khajavi & Partanen, *supra* n. 3.

⁷⁸ Christian Sandström, *Adopting 3D Printing for manufacturing – The case of the hearing aid industry*, Ratio Working Paper no. 262 (2015).

⁷⁹ Sonova Holding AG, *A Phonak, customized The advantage in the ear*, http://www.phonak.com/content/dam/phonak/b2b/C_M_tools/Spice_Generation/Documents/en/Brochure_BtB_Phonak_Custom_Products_GB_V1.00_028-0636-02.pdf (accessed 1 March 2017).

⁸⁰ Rakesh Sharma, *The 3D Printing Revolution You Have Not Heard About*, Forbes Tech, <http://www.forbes.com/sites/rakeshsharma/2013/07/08/the-3d-printing-revolution-you-have-not-heard-about/#1188dce721e1> (published 8 July 2013, accessed 1 March 2017).

⁸¹ Tarun Tampi, *Smartech Report: 3D Printing in Dental Market to Reach \$3.1 Billion by 2020* <https://3dprintingindustry.com/news/smartech-report-3d-printing-in-dental-market-to-reach-3-1-billion-by-2020-51971/> (accessed 1 March 2017).

⁸² Salmi M., Tuomi J., Sirkkanen R., Ingman T., & Mäkitie A, *Rapid tooling method for soft customized removable oral appliances*, 6 Open Dent J 85 (2012).

⁸³ Salmi M., Paloheimo K.S., Tuomi J., Ingman T., & Mäkitie, *A digital process for additive manufacturing of occlusal splints: a clinical pilot study*, 10 (84) Journal of The Royal Society Interface 20130203 (2013).

⁸⁴ Mäkitie AA., Salmi M., Lindford A., Tuomi J., & Lassus P., *Three-dimensional printing for restoration of the donor face: A new digital technique tested and used in the first facial allotransplantation patient in Finland*, 69 (2) Journal of Plastic, Reconstructive & Aesthetic Surgery 1648 (2016)

⁸⁵ M. Salmi, *Medical applications of additive manufacturing in surgery and dental care*, Doctoral dissertation, Aalto University (Unigrafia Oy 2013).

The traditional model in which the technology has matured involves a firm who sub-contracts the manufacturing of components with a service bureau using 3D printing. Typically, the 3D printing machinery is owned by the service bureau and the customer outsources the services. Most of the original equipment manufacturers or product development firms have relationships with 3D printing service bureaus. Therefore, this model serves firms by giving them access to a wider range of machines and materials without the need of capital investment to own tangible assets, such as machinery and secondary processes. In this model, the service bureau owns the risk for keeping up-to-date capabilities and serving the needs of their customers. On the other hand, the subcontractor loses the ability to grow knowledge within the company by adopting new methods of production. From the economic perspective, the operation of a production system is simple – the more the 3D printer is running with fully packed chambers the less the final cost per part is. In this regard, companies who cannot fill the whole capacity of the machine might be sharing 3D printing capacity with other companies or using service bureaus exclusively to fulfil their needs. Some of the most visible examples of contract manufacturing or ‘service bureaus’ using 3D printing are Materialise⁸⁶ and Protolabs⁸⁷. Materialise offers services with more than a hundred 3D printing machines able to process approximately thirty different materials (e.g. thermoplastics, thermosets, composites and metals) for multiple applications including prototyping, tooling and manufacturing. On the other hand, Protolabs has also an extensive portfolio of 3D printing capabilities and combines their offer with conventional manufacturing methods, such as machining or injection moulding. The business models of the presented companies have also diversified and matured. Manufacturing services are offered together with specific software solutions for dedicated industries, such as the medical industry. In this regard, companies can also offer 3D modelling. Modelling and consulting in novel technology applications have more additional value than providing only the manufacturing capabilities. The *Wohlers Report* estimates that in 2015 service providers generated USD 1,700 million sales, which only accounts for the part produced by 3D printing.

[D] 3D Printing as an Online Service: Digitalization of Manufacturing Services

This model is based on an online system where the orders are received online and the finished products are shipped to the customers. In this context, the process allows the upload of a digital CAD design and selection of the suitable 3D printing process. Online services in 3D printing certainly offer value added options to the community of users. The users can foresee the cost of the production, delivery time and in some cases select manufacturing site nearer the demand. Traditionally, this offer and order handling was carried out using email between two firms. Nowadays, this process can be automated and it creates a competitive advantage between firms that use and the ones who do not use this model. The use of online quoting systems for manufacturing, as well as manufacturing services, have shifted from a B2B context to a B2C

⁸⁶ Materialise, <http://www.materialise.com/> (accessed 1 March 2017)⁸⁷ Protolabs, <https://www.protolabs.com/> (accessed 1 March 2017).

⁸⁷ Protolabs, <https://www.protolabs.com/> (accessed 1 March 2017).

one. Originally, it served specific industrial customers, such as design and product development departments, to produce concept designs in short series and prototyping applications. However, new technological drivers, such as consumer-oriented digital manufacturing services, online design shops, affordable CAD modelling and 3D camera scanning, maker communities and online 3D product repositories have disrupted this business model – and B2B and B2C are increasingly converging in this area of competition.

Differences exist between the industrial and regular customers of online 3D printing services. For industrial users, the safety of their IPR is among the top concerns while tapping to this type of 3D printing services. Therefore, they prefer to have contract-based outsourcing of production. Moreover, confidence in the properties of the delivered parts can be another concern and, in the case of final parts, this can make the assignment of failure liability more complicated. In the regular customers' domain where the IPR confidentiality and parts reliability specifications are more relaxed, the industry is flourishing and new companies such as 3DHubs have emerged.⁸⁸ These companies tend to construct a network of 3D printing machine owners in every corner of the world and make them available to the potential customers. In this way the machine owners will be able to bring in revenue on their investment by utilizing their machine's free time. On the other hand, the customer will receive the required parts faster and with less shipping cost as the network enables the localization of production through connecting sellers and buyers in the same regions. As of early 2017, 3DHubs has over 7,100 3D printing service providers signed in around the world and an average delivery time of 2 days for production orders. In this type of business model, the network builder company acts as a middleman that enables communication and financial transaction between the buyers and sellers while directing a percentage of each transaction towards itself.

[E] Consumer 3D Printing and Retail

The availability of cheap desktop fused deposition modelling (FDM) machines and the evolution of the maker movement have created a fast growing market for consumer class of 3D printers. These machines typically cost less than USD 5,000 and have found their way into education, hobby and, to some extent, professional settings. Figure 2.7 illustrates the growth of this market and its impact on the 3D printing industry. In 2015, approximately 12,500 industrial 3D printing systems were sold, which represent 4.5% of 3D printing machines if we group them together with consumer-level 3D printers. Only 10 years ago, the 3D printing consumer market was non-existent, while, in the last year alone, approximately 280,000 machines were sold. What this figure does not explain is the impact in economic terms. In this regard, it is worth mentioning that the cost of an industrial scale AM system varies from USD 15,000 (e.g. more advanced plastic material extrusion systems) to USD 1.5 million (e.g. advanced metal 3D printing systems).

Today, it is estimated that the industry of consumer grade desktop 3D printing is creating a revenue of approximately USD 293.6 million on its own. Due to the fast growing rates of this industry segment, most industry players have also diversified their offering, acquiring many of

⁸⁸ 3DHubs, <https://www.3dhubs.com/> (accessed 1 March 2017).

the emerging startups. A similar trend will now occur for other technologies as several early vat photopolymerization (i.e. stereolithography or DLP) and powder bed fusion (i.e. selective laser sintering for plastics) patents have expired during the last 2 years.⁸⁹ It is expected that new companies will emerge with machines using these technologies, finding their way to the low cost consumer segment.

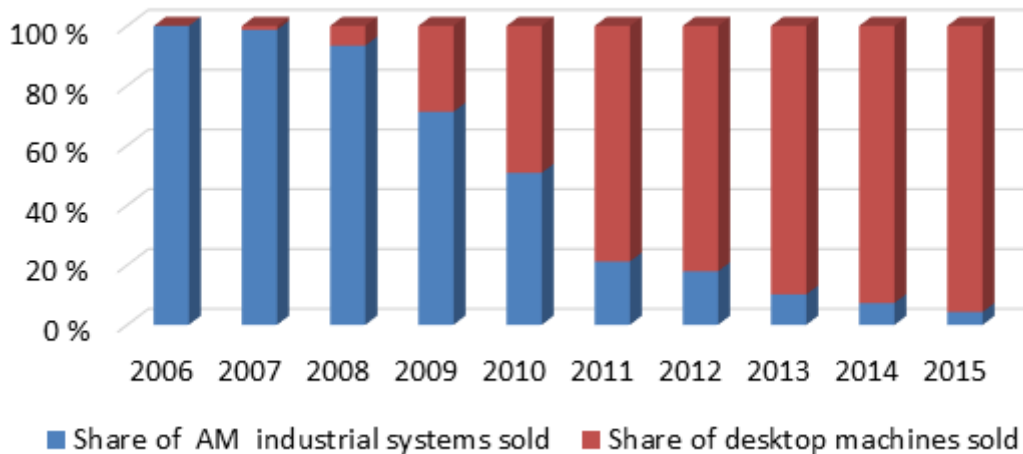


Figure 2.7: Unit sales growth for consumer grade and industrial grade 3D printers (data presented in percentage). Data adopted from Wohlers Associates, *Wohlers Report: Additive Manufacturing and 3D Printing State of the Industry* (2016).

§2.05 Emerging Business Models: What is coming next?

[A] Evolving Business Models

It is important to mention that most of the presented business players, as well as their working business models, are here to stay. What is coming next is an expansion of the market that will somehow reshape the existing business ecosystem. Today, it is rare to see the big players of the 3D printing ecosystem focusing only on one area of the business (e.g. 3D systems owning machines, software for CAD processing, service providing facilities or scanning equipment). Machine technologies, raw material development and software systems are being vertically integrated to a great extent. Major 3D printing companies have been in acquisition mode during the last 5 years. The clearest example of industry consolidation happened in late 2016, when GE planned the acquisition of two important machine vendors (Arcam AB and SLM Solutions Group AG) for metal 3D printing value-added applications in medical, aeronautics and space industries. GE today owns 76.16% of the shares of Arcam AB, which is a Swedish company that exclusivity owns the patent portfolio for electron beam melting (EBM) technologies. On the other hand, SLM Solutions Group is a producer of laser melting machines for metal-based 3D printing. The price tag for this acquisition was estimated to be USD 1.4 billion. However, as the

⁸⁹ John Hornick & Anita Bhushan, *3DPrinting Industry, More 3D Printing Patents Are Expiring Soon: Here's a Roundup*, <https://3dprintingindustry.com/news/more-3d-printing-patents-are-expiring-soon-heres-a-roundup-96561/> (accessed 1 March 2017).

acquisition of SLM fell apart, GE ended up replacing SLM for ConceptLaser. GE agreed to purchase 75% of the shares of this privately held German 3D printing firm for USD 599 million.⁹⁰

Another relevant trend is taking place with regard to the powder based machines for plastics. Expiration of patents allowed a number of startups to enter this closed market and try to create a foothold for themselves by offering much cheaper professional machines.⁹¹ For example, Norge,⁹² Sinteratec⁹³ and Sinterit⁹⁴ were among the first companies to try to challenge the established players. Among these, Norge Company had the most promising offering with regard to size, laser strength and cost. Despite that, Norge products never reached the market due to their acquisition by Prodways (one of the established AM machine manufacturers). However, we predict that it cannot stop other companies from disrupting this market and bringing down machine prices by reducing profit margins. The consequence of such events is vast and can bring Selective Laser Sintering technology to the masses in the same way as happened with FDM technology. SLS parts' characteristics – with regard to the material strength, precision and quality – can bring the manufacturing decentralization one step closer to reality, if it is coupled with affordability.

Moreover, the dynamism of this industry also generates new opportunities, especially in the software and system development side of the ecosystem. Things there remain unclear as the digitalization of manufacturing and the industrialization process of 3D printing systems is an undergoing challenge. Future interconnected, robotized and digitalized production systems will require new IT architectures and platforms creating opportunities for new disruptive business models.⁹⁵ In this regard, there are high concerns for cyber security and digital rights management in interconnected 3D printing manufacturing services. IP protection of geometry and metadata will need to be developed further to enable supply chains based on distributed 3D printing capacities.⁹⁶ With regard to IP protection systems and counterfeit recognition, emerging businesses are significant as they benefit the 3D printing industry ecosystem as a whole. For instance, any action for the simplification of liability assignment will potentially increase the manufacturers' trust in 3D printing processes. Implementation of methods such as the use of digital rights management software, quantum dots or blockchain databases to track, trace and distinguish the original 3D printed parts from the counterfeits can prove to be fundamental for the direct digital manufacturing of final parts. In the future, a customer with reverse engineering knowhow and 3D printing capability can become independent of an OEM as well as third party service providers in the lucrative aftersales market. This should ring the bell for the OEMs to

⁹⁰ Photonics Media, *GE Acquires Stake in Concept Laser, Arcam*,

<https://www.photonics.com/Article.aspx?AID=61484> (accessed 1 March 2017).

⁹¹ Brian Krassenstein, *First Ever Affordable SLS 3D Printers to Launch on Kickstarter Next Week by Norge Systems*, <https://3dprint.com/11787/ice1-ice9-sls-3d-printer-norge/> (accessed 1 March 2017).

⁹² Michael Molitch-Hou, *3DPrinting Industry, First Low Cost SLS 3D Printers Hit the Scene*, <https://3dprintingindustry.com/news/first-low-cost-sls-3d-printers-hit-scene-31351/> (accessed 1 March 2017).

⁹³ Sinteratec, <http://sinteratec.com/> (accessed 1 March 2017).

⁹⁴ Sinterit, <http://www.sinterit.com/> (accessed 1 March 2017).

⁹⁵ Robert Bogue, *What future for humans in assembly?*, 34 (4) *Assembly Automation* 305 (2014).

⁹⁶ Michael Burkett & Pete Basiliere, *What 3D Printing Means for Your Supply Chain?*, <https://www.gartner.com/doc/3234217?ref=ddisp> (published 1 March 2016, accessed 1 March 2017).

adapt their business models accordingly to be agile, flexible and information driven. As the profit margins of raw materials (e.g. the emergence of cheap raw materials such as the case of MetalYSIS for titanium and tantalium⁹⁷) and hardware solutions shrinks through time, the future business models will focus on wider applications of 3D printing (for instance to provide highly customized products).

[B] Digitalization of Manufacturing Operations: The Role of 3D Printing

The size of the 3D printing industry in the year 2015 was USD 5.2 billion,⁹⁸ which is less than 0.05% of global manufacturing market (i.e. about USD 11 trillion⁹⁹) in the same year. Looking at this number, one can quickly realize that currently the share of the 3D printing industry is quite marginal in comparison. However, what is relevant is the growth potential as technical limitations with regard to production cost, speed and parts' mechanical properties are overcome. After this, a number of serious applications in manufacturing can be unlocked. Only afterwards can AM play a major role in manufacturing and supply chains as it simply reduces the cost of operation. For example, in every spare part's supply chain, reduction of on-hand inventory (increased turnover) while keeping a high service level is of great importance. 3D printing can enable more effective and efficient spare parts operations. In spare parts operations, there is a need to support legacy products (in addition to the current ones) by providing a proper combination of parts, skilled work force and equipment to carry out a successful repair.¹⁰⁰ While spare parts demand unpredictability is a major challenge, 3D printing can reduce the capital tied to inventories and its carrying cost, as well as part's obsolescence, by a build-to-order scheme. Moreover, the service parts arrival to the repair site (response time) is kept at its minimum through a distributed deployment of 3D printers (less transportation).¹⁰¹

In addition to spare parts, in-situ production or build-on-location can be implemented for other items. In the future, it will be possible to produce parts in a geographically dispersed manner, increasingly facilitates products' customization and upgrade capability while reducing trans-shipment requirements. To enable in-situ 3D printing, methods to assure the safety of data in the cloud and to address product liability in case of a failure needs further development. Another interesting application of 3D printing will be in the new product introduction process – especially in the case of entirely novel ideas, for which historical market data is scarce or simply not available. To reduce the cost of failure, manufacturers can launch the product into the market (while the production batches are small and the demand for the product is still uncertain) utilizing 3D printing.

⁹⁷ MetalYSIS, *3D Metal Printing*, <http://www.metalYSIS.com/3d-metal-printing> (accessed 1 March 2017).

⁹⁸ Wohlers Associates, <https://wohlersassociates.com/press71.html> (accessed 1 March 2017).

⁹⁹ The World Bank, *Manufacturing, value added (% of GDP)*,

<http://data.worldbank.org/indicator/NV.IND.MANF.ZS> (accessed 1 March 2017).

¹⁰⁰ Morris A. Cohen, Narendra Agrawal & Vipul Agrawal, *Winning in the aftermarket*, 84 (5) Harv. Bus. Rev. 129 (2006). Available online, <https://hbr.org/2006/05/winning-in-the-aftermarket> (accessed 1 March 2017).

¹⁰¹ Siavash H. Khajavi, Jouni Partanen & Jan Holmström, *Additive manufacturing in the spare parts supply chain*, 65 (1) Comput. Ind. 50 (2014); François Pérès & Daniel Noyes, *Envisioning e-logistics developments: Making spare parts in situ and on demand. State of the art and guidelines for future developments*, 57 (6) Comput. Ind. 490 (2006).

3D printing will allow the producer to access the market faster with much lower risk while also allowing the utilization of customer feedback in future batches since design modification is possible. This allows manufacturers to shift to traditional tooling when the product concept receives acceptance in the market and expected demand levels are met.¹⁰² The simplification of supply chains is another novel benefit of 3D printing for final parts production, which expands its use in complex manufacturing. It offers to save time¹⁰³ and money (lower labour requirements and waste occurrence) while also improving product quality. Moreover, the possibility of eliminating tooling altogether through the use of 3D printing and component consolidation (reduced stock keeping units and less intermediary processes such as assembly) are other benefits. This is significant for advanced manufacturing in aeronautics and space industry,¹⁰⁴ among others. Another aspect of 3D-printing-enabled supply-chain simplification deals with design for performance (topological optimization) with less concern about the manufacturability. This saves raw material through parts' weight reduction and potentially expands product life-cycle.

3D printing can unlock production capacity pooling through a virtual, interconnected factory setup. This model can increase a firm's flexibility while saving costs through the full utilization of production equipment. Manufacturing capacity sharing may take place as companies with machines start to share their unused capacity under different types of agreements. Alternatively, it might take place as an OEM or a third party service provider configures a network of 3D printing machines to provide production capacity as a service.¹⁰⁵ In peer-to-peer (P2P) capacity pooling, companies with excess production capacity participate in the pooling network if they are compensated for doing so or if they require more capacity at geographical locations in which other members are present in. Moreover, the size and reach of a company will potentially be effective in inter-organizational agreements. While in a third-party capacity provision setting, each client company might be active in a different industry and a distinct geographical location, which makes it difficult for the service provider to establish a centralized production facility trying to serve all of the locations with acceptable service levels. Thus, it can take advantage of production distribution and locate the 3D printing machines in optimal proximities to customers' facilities in order to be profitable and provide high service levels.

[C] Technological Challenges Ahead: Industrializing 3D Printing

The industrialization of 3D printing requires standardization. In the early days, this was not required since the parts were only used in prototyping. Standardization of processes and materials will allow the industry to deliver a common message. However, the reality is that major companies using 3D printing for end use applications have created their own guidelines

¹⁰² Siavash Khajavi, Jouni Partanen, Jan Holmström & Jukka Tuomi, *Risk reduction in new product launch: A hybrid approach combining direct digital and tool-based manufacturing*, 74 *Comput. Ind.* 29 (2015).

¹⁰³ Jan Holmström, Matthias Holweg, Siavash H. Khajavi & Jouni Partanen, *The direct digital manufacturing (r)evolution: definition of a research agenda*, 9 (1) *Oper. Manag. Res.* 1 (2016).

¹⁰⁴ GE, *Advanced manufacturing is reinventing the way we work*, <http://www.ge.com/stories/advanced-manufacturing> (accessed 1 March 2017).

¹⁰⁵ Jan Holmström, & Jouni Partanen, *Digital manufacturing-driven transformations of service supply chains for complex products*, 19 (4) *Supply Chain Management: An International Journal* 421 (2014).

for materials and processing. In highly regulated industries, material and process data sheets have to be comparable as testing and certifications are crucial to adopting novel processes or materials. In this regard, metal production for end-use applications has induced many standardization activities allowing the development of quality control and inspection methodologies. Standards are a necessary part of the evolution of 3D printing as a production method. 3D printers have technical limitations related to build speed, geometrical stability and build volume. Low build speed increases the price of the product and reduces productivity. Larger build volume allows for making larger parts and new applications, as well as making more small parts during the same production run. Productivity is important when 3D printing is compared to traditional manufacturing methods. Another downside is low geometrical stability and warpage after the processes or from environmental aspects such as UV-radiation from the sun. In end-use applications, it might be the case that parts must endure tens of years under environmental conditions and need to keep their stability all that time. Material characterization such as fatigue performance or thermal fatigue is required before parts can be put under rough conditions.

The most experienced designers have always designed against the limitations of traditional manufacturing methods. 3D printing opens new opportunities but also new limitations for designers. It is hard to change the mindsets of those experienced designers to design with fewer limitation and this is the reason why the potential of 3D printing is so hard to utilize. New design might also need new kinds of design tools, such as topology optimization and simulation software. Education for 3D printing is still rare and scattered. The industry might have a hard time finding skilled workforce, especially for the design phase, which is the basis of utilizing 3D printing's full potential. In many 3D printing processes, manual work is needed in preparation of the process and the post-processing of the parts. In the future, the industrialization of 3D printing will require a combination of the technology with manufacturing cells, robotics and automation. This might automate secondary operations, and reduce manual work and costs. The first implementation of these idea was seen from 3D Systems, where they combined vat-photopolymerization with a fully automated production and integrated secondary processes.¹⁰⁶ Additional developments include a continuous 3D printing process concept created by TNO.¹⁰⁷ More and more of these kinds of solutions will open up new markets for 3D printing in high scale manufacturing.

[D] Is the 3D Printing Industry short of money?

After the hype around 3D printing technologies, 2014 was the beginning of a two years decline in the share values of the major 3D printing machine vendors (i.e. 3D Systems and Stratasys). The expectations also decreased and the industry began to be more critical towards novel

¹⁰⁶ Michael Molitch-Hou, *3D Systems Unveils Figure 4 Robotic SLA 3D Printer at AMUG*, 3DPrinting Industry, <https://3dprintingindustry.com/news/3d-systems-unveils-figure-4-robotic-sla-3d-printer-at-amug-75805/> (accessed 1 March 2017).

¹⁰⁷ Ir. Frits Feenstra, *Continuous 3d printing: faster, cheaper and more flexible*, TNO innovation for life, <https://www.tno.nl/en/focus-area/industry/flexible-free-form-products/additive-manufacturing/continuous-3d-printing-faster-cheaper-and-more-flexible/> (accessed 1 March 2017).

applications. Industry experts, as well as research institutions, admit now that the expectations were set much higher than the realistic applications of the technology could produce. Despite all the hype and reality checks during the past years, there are market segments that have continued growing, empowering the industry at large (e.g. powder bed fusion systems and high-end metal applications). Projections describe that the industry growth will continue steadily as the technology is integrated by major OEMs to work in parallel with conventional production lines. Investing activities and big acquisitions have not stopped. To some extent, the industry has refocused, attracting the attention of investors to drive the technology towards the industrialization of high value manufacturing applications (e.g. aerospace, automotive, manufacturing, medical and dental). In this regard, investors have supported several start-up companies for new technologies. This supports, for example, high speed sintering solutions;¹⁰⁸ Carbon 3D's vat-photopolymerization, which received USD 100 million;¹⁰⁹ or XJet's metal inject technology, which was announced to have raised USD 25 million in a funding round led by the Catalyst CEL Fund, and Autodesk.¹¹⁰ Several countries have started dedicated investment projects to develop 3D printing capabilities at the national level. For example, in France, an investment of EUR 45 million went into research projects focused on AM and the Netherlands is investing EUR 134 million in research and industry projects for technology transfer. The technology is now classified as a key enabling technology (KET) for the future to come. The European agenda in research has allocated considerable financial resources to AM related research, and technology development and innovation activities have become the biggest ever EU funded topic since FP7 up to 'Horizon 2020' (H2020), with nearly EUR 80 billion of funding available over 7 years (from 2014 to 2020).¹¹¹ Other countries have similar initiatives on the way. However, the biggest move in the industry came from a major OEM when GE acquired two of the major AM machine vendors to serve its businesses, with the ambitious goal of producing a total of 100,000 3D printed parts in its aeronautic business alone by 2020. In fact, the development in 3D printing are not only concentrated in western countries. To this end, China, the world's centre of mass manufacturing, has also looked at the technology as a solution for the future, revealing that it will overtake the US in terms of 3D printer sales this year.

§2.06 Conclusions

This chapter was focused on evaluating the underlining business models of 3D printing industry. First, we started by presenting the current paradigm change from the third to the upcoming industrial revolution, which will be triggered by the internet and will redefine communications

¹⁰⁸ Andrew Bounds & Tanya Powley, *3D printer aims for production line speed*, <https://www.ft.com/content/f14a1df4-0881-11e5-b38c-00144feabdc0?siteedition=intl#axzz4JbSYJqQz> (published 2 June 2015, accessed 1 March 2017)

¹⁰⁹ Jonathan Vanian, *Google Ventures just led a \$100 million investment in this hot startup*, <http://fortune.com/2015/08/20/google-invest-carbon3d/> (published 20 August 2015, accessed 1 March 2017).

¹¹⁰ Michael Petch, *A new 3D printing technology, interview with Xjet's Dror Danai*, <https://3dprintingindustry.com/news/new-3d-printing-technology-interview-xjets-dror-danai-94941/> (accessed 1 March 2017).

¹¹¹ European Commission, Executive agency for SMEs, *Identifying current and future application areas, existing industrial value chains and missing competences in the EU, in the area of additive manufacturing (3d-Printing): Final Report* (2016).

between humans and machines, contributing to structural changes of social relationships for both consumers and corporations. To this end, companies will need to organize their operations to have a better response to markets' changing needs. In this regard, 3D printing technologies clearly benefit from strategies based on economies of scope and customer integration in the value chain. 3D printing technology has reached frontiers well beyond its initial application. The technology is increasingly used as an end-manufacturing solution in many sectors as the 'scale-scope dilemma' can be solved, in which product variety can be higher without cost penalties. Therefore, 3D printing is a key enabler for the following use cases:

- rapid prototyping, innovation and early stage product development;
- rapid, short series and bridge manufacturing and tooling applications;
- decreased weight and optimization of key components for improved functional performance (e.g. part consolidation, topology optimization, heat and mass transfer optimization);
- consumer involvement in the definition of new product-services (e.g. prosumerism and co-creation);
- mass-customization of consumer products, after sales-customization industry and medical applications (e.g. user-fit requirements, ergonomics and aesthetics);
- digitalization of inventories and supply of spare-parts;
- production near demand and on-demand;
- distributed and reconfigurable supply chain implementation; and
- online manufacturing capacity transactions.

This chapter showed 3D printing as an ecosystem and depicted its interplays between different industry enablers in the uptake of 3D printing, as well as the role of consumers, innovation and entrepreneurship. We concluded that companies that are able to obtain value from the technology exist across multiple markets, such as the medical industry, manufacturing, information and communication technologies, consumer products, consultancy, services, and retail, among others. In addition, there are multiple technical elements that merge in one single ecosystem, hindering the diffusion of 3D printing technology in current industrial conglomerates. Firms' adoption of 3D printing technologies is determined by the pace and breadth of innovation diffusion (i.e. changes in the organization or change management). These challenges raise questions about the competitiveness of firms which are considering to adopt the new technology, generating a set of trade-offs between competition versus innovation dependence in the diffusion of the technology. Companies today find great incentive in the adaptation to 3D printing technology. However, by doing so, their competitive strategies may be restrained temporarily while the learning curve is overcome, locking part of their R&D capabilities to understanding the role of the technology for the organization. In the easiest scenario, 3D printing only requires a CAD file shared freely on the internet ready for manufacturing near demand on a desktop machine. On the other end, regulated industries will be required to implement more complex

hybrid cross over solutions to merge 3D printing technologies with conventional methods of production and quality control.

The fourth section of this chapter explored the basic business models that have generated growth and diffusion of the 3D printing technology. Here, a detailed list of players was presented including machines, material and system suppliers; service bureaus; consumer 3D printing companies; and digitalized manufacturing services. To this end, specialized software becomes one of the interlocking mechanisms to drive the technology to massive adoption. It facilitates the flow of information between parties towards a virtually interconnected factory in which manufacturing can be traded as a service. However, existing challenges related to digital rights and IP management become critical in this scenario and are hindering the digitalization of manufacturing services in many firms. The fifth section in this chapter presented the emerging business models and future technology applications. We mentioned that most of the presented business players, as well as their working business models, will prevail. What is coming next is an expansion of the market that will somehow reshape the existing business ecosystem. In this regard, the role of large industrial conglomerates or major OEMs is important as they can reshape the ecosystem creating new verticals (e.g. GE's recent acquisitions).

Without paying too much attention to the current physical constraints and the limitations of the technology (e.g. build speeds, productivity issues, build volumes, repeatability and material limitations), incremental technology improvements will unlock extensive applications for this technology as the production of final parts currently has a large share of 3D printed products. With this in mind, current business issues, such as unpredictable demand patterns, challenges for logistics flow optimization, the need for customized goods and services, shorter product development cycles, shorter product life cycles and customization in manufacturing will be addressed by new development and implementation of 3D printing technologies. 3D printing will have a major role in the future of manufacturing and supply chains as it simply reduces the cost of operations and improves product-service performance. For instance, in the spare parts supply chain, 3D printing offers the following benefits: reduction of inventory, production on-demand and near-demand, and simplification of supply chains. With 3D printing technology, the gap between the virtual and physical world becomes narrower as it has the potential to digitalize, connect and simplify company operations.

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