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3D printing and applications: academic research through case studies in Finland

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Abstract

This research presents a comprehensive view of 3D printing technologies and their evolution. Additionally, it provides a Nordic perspective on the topic by summarizing project based research conducted in Finland. Expert interviews and research data extracted from case studies are analysed to cover topical areas on additive manufacturing transferability. The contribution of this research is to combine industry case research with expert interviews, and finally present recommendations to promote technology transfer.

The synthesis of the presented cases allowed us to conclude that additive manufacturing will offer greater possibilities in applications when: (1) innovation and design processes need to be enhanced, (2) customization is an advantage, (3) supply chain needs to be flexible, simplified or compressed, (4) material usage and inventories need to be reduced, (5) energy usage and waste in manufacturing have to be minimized and (6) product performance has to be optimized.

In consequence, to promote technology adoption and competitive advantage in companies - policy actions should be focused on increasing input for innovation and R&D, improving and increasing the supply of skill as well as generating and exploiting the connections and complementarities of country-specific academia, research institutions, industrial clusters and funding bodies.

Keywords: Additive manufacturing; 3D printing; Digital manufacturing; 3D printing applications; Innovation policies

1 Introduction

During recent years, 3D printing (3DP) (also known as additive manufacturing [AM]) technologies have become mainstream. The expiration of essential technology patents, as well as the development of new materials along with innovative additive processes, has attracted the renovated interest of industry, academia and public media. The claim is that AM can replace conventional manufacturing solutions (Campbell, Bourell & Gibson, 2012) and reinvent the way products are designed, manufactured and distributed globally (Khajavi, Partanen & Holmström, 2014). Today the technology has a strategic position in the definition of innovation policies on a global scale. AM is considered an enabler for companies to gain competitive advantage. Thus, giving them a new range of opportunities in terms of quick product and production line reconfiguration, distributed manufacturing, customization and personalized product development. In the future, AM systems will produce the key components of a product, driving the digitalization of design and manufacturing environments to the next industrial revolution (Horizon 2020 FP7, 2014). On the negative side, the hype is much more visible than the reality. Industry and academia have identified intrinsic drawbacks to AM technology. The first issue is linked to the limited characterization of the additive machines and materials. Standardization of the technology, processes and material is at early stages. Tackling this issue is fundamental in order to make AM technology accepted by regulated industries (such as the aeronautic, aerospace, automotive, medical and manufacturing industries). With this in mind, there is a lack of research that would help understand the societal, economic and technical implications of the technology for modern organizations (Flores Ituarte et al., 2015).

The second drawback is related to the reliability and repeatability of AM processes. Improvements in quality, performance validation and expanding materials options as well as the size capabilities of new-generation machines are likely to impact positively as development in this area is in the early stages (Guo & Leu, 2013). Finally, there is a lack of understanding of the technology from the practical application perspective. This is still vague among the industry professionals, partly because the relevant standards only define AM technology as machine process, not depending on the application areas in which the technology is being used. In addition, recent studies show that the AM industry is still optimizing costs structures (i.e. those of machine costs, material costs and labour costs), this being a significant factor affecting whether companies adopt AM technologies or not (Thomas, 2013). Reducing these costs may boost the AM industry and truly drive the use of AM technologies as a production method in the forthcoming digitalized era. However, currently the shift towards AM as a production method is still not fully clear in traditional design and engineering industries as the positioning of AM technology as something that creates value in company operations is still vague.

In this regard, this work will present ongoing industrial, medical and design case study research of early adopters in Finland. Based on this, we will shed light on future policy strategies for Nordic countries. This work intents to synthetize key enablers for the successful technology adoption in industry to connect with policy strategies which need to be articulated in order to benefit from 3DP technology.

2 Materials and methods

The research methodology is grounded on case study research design and action research, and hence involves a mix of quantitative and qualitative research methods. Quantitative data presents AM market evolution, which has been obtained by studying industry-specific market reports. In this case, the data presented in Figure 1 and Figure 2 has been compiled using Wohlers Report (2000–2015). In addition, the empirical case research has been collected in a series of case studies starting in 2010. Qualitative data was included through two non-structured interviews with industry technology users and academics who have worked in AM application research for the past 20 years. The contribution of this research is to link case research with industry data (Eisenhardt, 1989) in order to finally build new theory on strategic implications for policy makers and companies.

3 3D printing: the industry, applications and market evolution

Traditionally, industrial applications of 3DP/AM are linked to the early stages of the design and product development process. The technology helps companies in the iterative design process, early stage product functionality testing and also as a tool for product designers to communicate ideas. ISO/ASTM standard defines this as rapid prototyping (RP). In addition, the tooling industry uses AM to produce parts that serve as the actual tools or tooling components, such as molds or mold inserts (e.g. patterns for casting applications or wax models for investment casting). This process is defined as rapid tooling (RT) (ASTM International, 2013). Finally, the use of AM 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) (Hopkinson & Dickens, 2003).

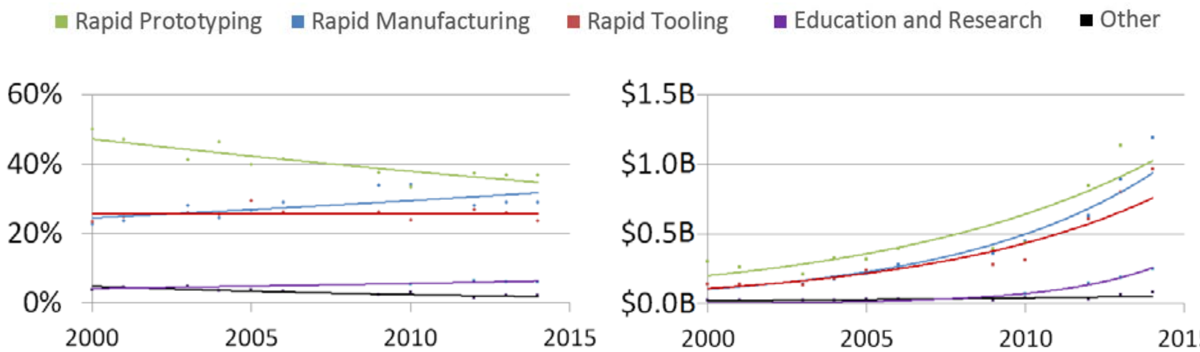

Figure 1 – Leftmost: the percentage of usage. Rightmost: revenue in US$ billion per industrial application. Adapted from Wohlers Report (2000–2015).

By looking at the trend lines presented in Figure 1, the AM market (consisting of all products and services worldwide) grew 35.2% from 2013 to 2014, representing $4.1 billion. The average annual growth during the past 26 years has been 27.3%, of which half of revenue stream have always been linked to RP activities, whereas RT and RM applications cover the other half. Trend lines show that AM technology is evolving towards the production of end-use applications, also known as RM. Comparing this data with Finnish industrial ecosystem, automotive and aerospace industry activities are minor. Whereas, medical and dental industry – and especially consumer products and electronics, and industrial and business machines – are present. According to the data, the mentioned industrial sectors are driving AM revenue growth internationally, covering approximately 80% of AM applications.

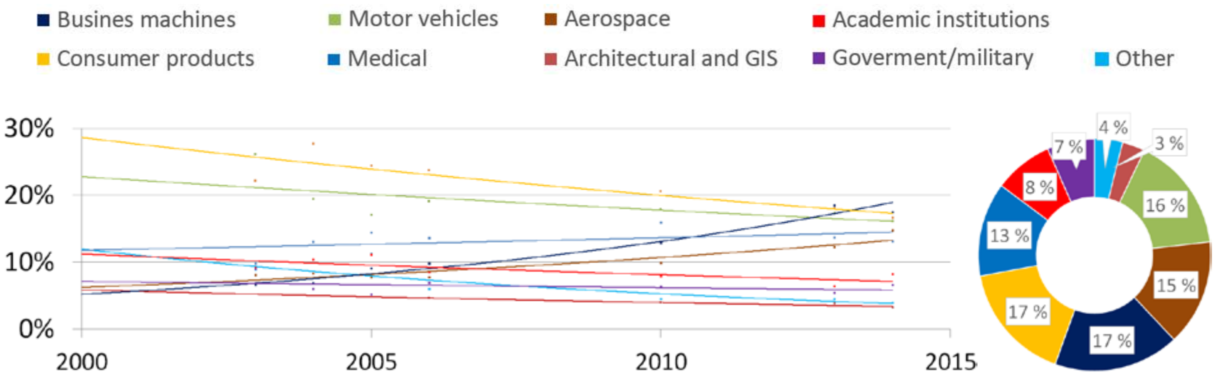

Figure 2 – The percentage of AM usage per industrial sector. On the left: the historical trend line. Rightmost: 2014 data pie chart. Adapted from Wohlers Report (2000–2015).

In Finland, AM technology is used mainly for RP. In comparison with international trends, there is still an untapped potential for RM and pre-series production. Expected improvements in the technology reveal a potential cost reduction of about 60% in the next five years and another 30% within the next 10 years (Roland Berger, 2013). These reductions will significantly boost the market for RM applications.

4 Innovation policy challenges in the Finnish context – experts view

The findings of the interviews pointed out that the penetration of the technology in the Finnish industrial ecosystem is performed in a non-structured way. Typically lessons learned have had a limited impact, making the reuse and transfer of the gained knowledge difficult. In addition, companies have had little willingness to cooperate and share knowledge. Another relevant aspect pointed out in the interviews is that the AM supply chain is in its early stages, slowing down technology transfer. At a national level, AM service suppliers do not have access to all the state-of-the-art machinery and materials.

In addition, experts argue that there is the problem of weak internal manufacturing “cluster” structures. In the 1990s the so-called Nokia cluster boosted the Finnish AM industry and Finland was at the cutting edge of AM upstream sectors. For example, the Nokia prototyping facility was known as a leading AM applications developer and EOS Finland (i.e. Electrolux – Rusko at that time) started its Direct Metal Laser Sintering process development. Already in the 90s injection molding and metal casting companies developed AM based tooling applications. In the 2000s Nokia and its supply chain started to decrease in Finland with the offshoring of manufacturing. At the same time international AM technology and business development started to grow fast, leading to the current situation in which Finland does not have any specific position in the AM industry.

Based on the interview data, to promote innovation and new business models taking advantage of AM technologies, short-term and midterm innovation policies should focus on developing scenarios for rapid technology transfer, using and empowering the existing industrial ecosystem, and promoting AM as an upcoming manufacturing solution for industry. Traditional product development companies must be aware of this scenario and policies should facilitate the integration of the technology, firstly, by targeting potential early adopters and technology enthusiasts, and secondly, by expanding support towards more conservative and sceptical industries. Seems trivial that final production using AM will be always be linked to variables, such as the complexity of the geometry, production volumes and supply chain factors. Therefore, AM systems will hardly be competitive in scenarios in which the product has been designed to be conventionally manufactured and conventionally distributed.

5 Case study research and empirical work

The design and product development implications of AM in industry can cover several disciplines, such as industrial design or mechanical engineering design. Recent research has expanded RM applications into four sub-categories that cover four applications domains: (1) user-fit requirements and ergonomics, (2) improved functionality or product performance, (3) parts consolidation and (4) aesthetics (Campbell et al., 2012). The following two subsections will cover parts consolidation and the product functionality applications of the technology.

5.1 Assembly and parts consolidation

The case presented in Figure 3 shows the manufacturing for end-use application of a nozzle for an air flushing application. The finding from this case helped the company to simplify their supply chain, reduce material usage and inventories as well as energy usage during manufacturing operations. The new construction has reduced the amount of components to a single unit. The original design was composed by the assembly of seven parts (i.e. aluminium and plastic molded components). The AM process used was selective laser sintering (SLS) and the material is nylon (PA12). The original production cost was €400 and currently the cost has been reduced to €100, maintaining a similar product lifetime as well as performance in comparison with the original.

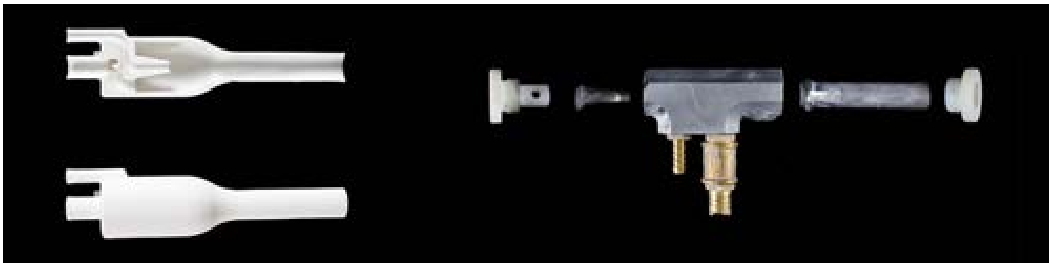

Figure 3 – Product components for an air flushing device (courtesy of Alphaform OY).

5.2 Improved functionality or product performance

Improved product functionality using AM technologies covers several disciplines of mechanical engineering. For instance, structural optimization or topology optimization for part strength or stiffness is one of them (Wang et al., 2013). Another application also looks at geometry optimization for fluid dynamics applications. In this regard, geometries can be completely redesigned to maximize performance (Rosen, 2014). In addition, heat exchangers can also be redesigned to optimize their efficiency (Aslam Bhutta et al., 2012). In the case presented in Figure 4, the presented geometry has been designed and manufactured with the aim of integrating all the complexity and functionality of the mechanisms into a single element while decreasing its volume. This element is part of the coin sorting system that can be found in ticketing systems of public transport. Production volumes of the element fluctuate from 100 to 600 units per year, making AM a cost-effective solution. The general construction of the device requires multiple connection points for sensing, optics and servo motors, as well as moving parts that provide the final performance of the product. To produce this geometry, the molding of milling technologies would have been impossible and the part was manufactured using SLS and nylon (PA12) material. The learning outcomes from this case helped the company to increase product performance of the overall assembly while simplifying their supply chain, tooling inventories and energy usage of manufacturing operations.

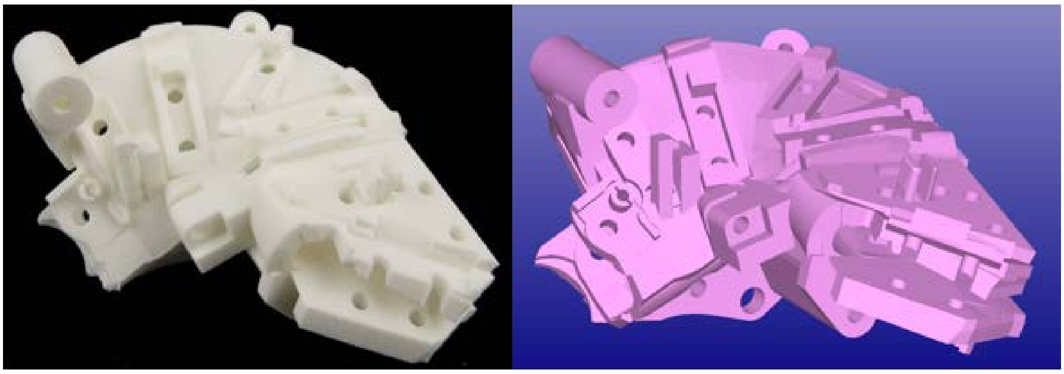

Figure 4 – A product component for a coin sorting machine (courtesy of Genimate OY).

Research into the medical applications of AM has classified the technology in five subgroups: (1) medical models for pre and post-operative planning, (2) medical aids, orthoses, splints and prostheses, (3) tools, instruments and parts for medical devices, (4) inert implants and (5) bio-manufacturing (Tuomi et al., 2014). AM is well suited for the manufacture of complex, organic-shaped geometries that cannot be easily produced using conventional methods, such as formative or subtractive techniques. Furthermore, customized and fully ergonomic solutions are manufacturable using an individual person's imaging data. Customized solutions go hand in hand with low volume production, thus also making solutions feasible in terms of the production cost (Salmi et al., 2012). The following two sub-chapters will cover case research in pre-operatory planning applications and tools or instrumentation for medical devices.

5.3 Medical models for pre-operative planning

During collaborations of Aalto University, hospitals in the metropolitan area of Helsinki, individual surgeons and clinicians, several pre-operatory models have been prepared for the planning of complex surgical problems. One approach to utilize modern medical imaging modalities to create digital models is based on multimodal imaging with computed tomography (CT) and magnetic resonance imaging (MRI). A simulated case of such is presented in Figure 5 – due to patient privacy reasons, this is not actual clinical data, but a representative example. The figure shows a CT image of a patient on the left, a digitalized model with MR-imaged lesion (in red) in the middle, and the picture of the 3D printed part used for pre-operatory planning on the right.

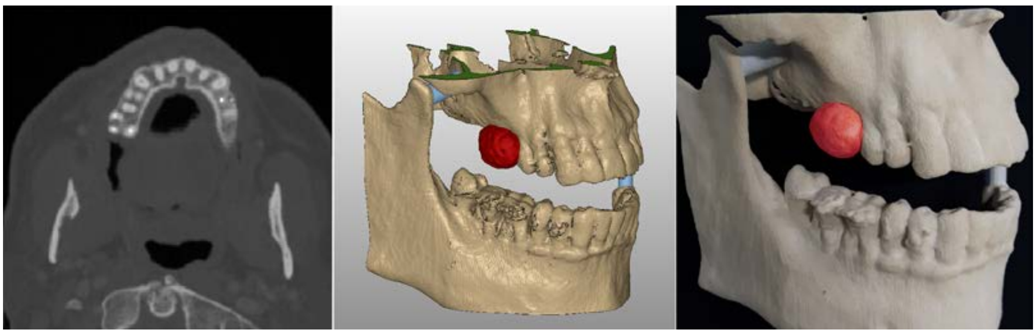

Figure 5 – A simulated case of image fusion, and 3D printed part of a preparatory model for patient affected by maxillofacial tumour.

The process flow required to generate the 3D printable data extracted from the medical imaging of the patient – the most commonly used imaging modality is CT, which provides data of the hard-tissue interfaces. Other modalities – such as MRI, ultrasound and nuclear isotope imaging methods – have been used to generate data on soft-tissue interfaces. The data is then fused and digitalized to a 3D printable format. Prior to the clinical application, the model might need post-processing, such as surface polishing or sterilization. The generated model was produced using a binder jetting process, as it allows to print in color, and then hardened with an epoxy-like binder. Colors are used to highlight the region-of-interest – the lesion – for pre-operative assessment of the clinical situation, enabling the surgeons and other clinicians to enhance visuospatial understanding of custom patien especific clinical condition as well as the tasks required for optimal patient recovery.

5.4 Tools, instruments and parts for customized medical devices

AM tools and hardware for medical applications can be used improve the efficacy of a medical or surgical procedure; the technology allows for the cost-effective design and production of custom-made and even patient-specific instruments. The paradigm of mass-customization from patient specific data was explored and tested with medical experts using clinical data. The case presented in Figure 6 shows a prototype of a medical instrument used in mandible fracture surgery, which was manufactured in stainless steel (PH1) using direct metal laser sintering. The device was manufactured in three separate units and the instrument itself was then manually assembled. The idea of this study was to use standard instruments with interchangeable tips or handles that can be designed using patient-specific data and produced cost-effectively with AM technology.

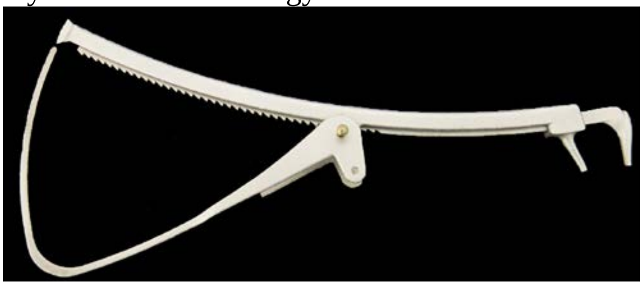

Figure 6 – The prototype of mandible fracture forceps (Kontio et al., 2013).

The classification of design applications is not as rational as in the previous application domains (i.e. medical and industrial applications). Nevertheless, design applications are at the boundaries of art, science and technology. The case research presented in this work only covers two cases: RT applications (or, more specifically, investment casting techniques) and research on design through process, which is related to design for additive manufacturing (DFAM) rules.

5.5 Rapid tooling and investment casting for jewellery design

Figure 7 shows one of the designs, the wax printing process and the final result (the design piece manufactured in bronze). The technique allowed to speed up the process from idea to materialization enhancing the design and innovation process in jewellery design. Indirect molding using this technique allows the designer to create fully organic and miniaturized geometries that can hardly be produced using other methods. The presented case was formulated during the collaboration of ADD LAB, Kalevala Koru and artist Katrin Ólína. Several designs were originated using a parametric 3D model based on a self-replicating primitive geometry.

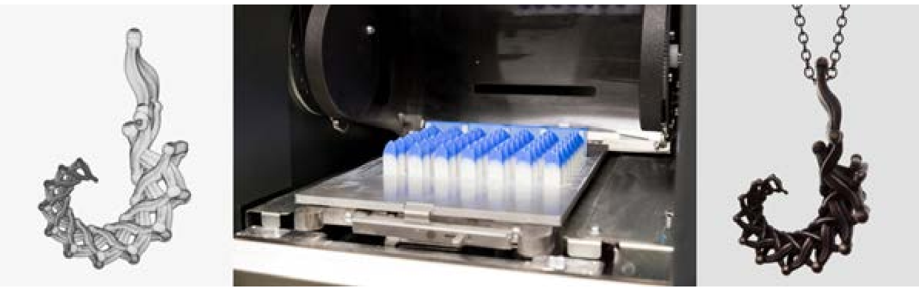

Figure 7 – *Primitiva-Talisman*. Left to right: the 3D parametric design, wax printing for the investment casting process and the produced bronze design. (Courtesy of Katrin Ólína and Kalevala Koru.)

5.6 Design through process – experimental research

Figure 8 shows three early stage experimentation results in the process of clay extrusion. The technique allowed to speed up the process from idea to materialization enhancing the design and innovation process in experimental research. Ceramic extrusion is a fairly new exploration in the field of ceramic design; the machine controlled material extrusion process allows possibilities to manipulate the input parameter, such as the material flow or deposition path, to yield different design results. Software and machine controlled processes gives a new ways to materialize ceramic components and form finding in the design process.

Figure 8 – Experiments with extrusion of ceramic materials (courtesy of ADDlab).

6 Conclusions and future perspectives

Base on the case research findings and synthesis, implementation of AM will offer greater possibilities in the following scenarios: (1) when innovation and design processes need to be enhanced, (2) when customization is an advantage, (3) when the supply chain needs to be flexible, simplified or compressed, (4) when material usage and inventories need to be reduced, (5) when energy usage and waste in manufacturing have to be minimized and (6) when product performance has to be optimized. In the midterm and long-term view, AM will replace conventional manufacturing in cases where technology users can clearly benefit from the mentioned scenarios.

Trend lines, such as that presented in Figure 2, show how, globally, the industrial business machine sector has the technology rapidly in the past 10 years, with it today representing 17% of AM applications share. The healthcare, medical, design and consumer electronics industries cover 30% of applications and altogether represent 47% of AM application share globally. These three sectors are a fundamental part of the Finnish national GDP, accounting for approximately 25% of it in 2014 (OECD, 2014). Taking into account that manufacturing activities in Finland had stopped declining after the crisis (European Commission, 2015) and considering the high number of Finnish SMEs with short series productions, authors believe that the competitiveness can be improved by adopting digitalized knowledge-based AM design and production methods. However, positive signs and technological promises have no value if the industry lacks a strong AM knowledge-based structure. To address this issue, future funding platforms have to be linked to technology advisory services. AM technologies and applications are diverse and require a different set of skills for each application domain. Therefore, academia, design and research institutes should provide technical assistance in AM technology readiness evaluations, consultancy, mentoring and other services in order to support enterprises in the adoption of new AM processes while reducing the financial risk for early users providing external R&D capabilities.

The answer to the question of *AM as truly a game changing technology for the manufacturing industry?* Will be “No” if industry is expecting a sudden change. The change will happen when AM technology is integrated line in line with conventional manufacturing methods and penetrates regulated industries. Although, the shift to this model will be slow, it will be disruptive in many ways. AM will create a competitive gap between those who take risks and test the technological capabilities today and those who take a conservative position and act as followers. With this in mind, policy action need to be targeted to intervene on the supply side of innovation (i.e. public interventions that seek to support the generation and diffusion of innovation in companies) as well as on the demand side of innovation (i.e. in education, R&D organizations and the industrial ecosystem).

In this regard, authors recommend the following three level policy strategy:
(1) Increase input for innovation and R&D. A long-term view of supply-side policies needs to be planned to increase input for innovation to create new intellectual property rights through basic R&D. Intellectual Property protection of technology applications can become advantage for companies, allowing them to find their killer applications using 3D Printing.
(2) Improve and increase the supply of skill. The supply-side policies need to focus on developing skilled workforce on digital manufacturing tools. Schools have to adapt their curricula to integrate an updated view of the technology in product design and manufacturing operations. Companies should also promote continuous professional technical education at the same time.
(3) Generate and exploit connections and complementarities. Gaining competitive advantage in companies will require policies to promote AM applications and technology transfer. Building bridges between academia, research institutions, industrial clusters and funding bodies

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Disclaimer

Certain company names and technologies are mentioned in the text in order to add clarity and specify the technical procedures and equipment used. In no case does such identification imply recommendation or endorsement by the authors, nor does it imply that they are necessarily the best available options.

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