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Economic Implications of Additive Manufacturing and the Contribution of MIS

[Grundtext]

1 Introduction

Additive manufacturing (AM) – also known under the umbrella term '3D printing' – denotes a family of manufacturing techniques that allow for the generation of arbitrary physical objects layer by layer from digital 3D blueprints. Although several companies have used AM in prototyping for more than 25 years, it was only recently that the techniques gained the attention of the broader public to the point of enthusiastic reports in the mass media. The current hype surrounding AM, not least driven by a number of expiring key patents, holds promise of setting off a new industrial revolution. Several market figures and forecasts seem to support this view. In 2013, the market for AM, including all products and services worldwide, grew to $3.07 billion with a compound annual growth rate (CAGR) of 34.9%; experts estimate the size of the AM market in 2021 at $10.8 billion (Wholer and Caffrey 2013). Despite this economic potential, research on AM has so far mostly been limited to the engineering disciplines focusing on methods and materials for the actual manufacturing process. In contrast, research on managerial opportunities and implications is still sparse.

The high expectations regarding the future impact of 3D printing are based on some fundamental differences between AM and traditional forms of goods production. Manufacturing systems in general can be distinguished along two major dimensions: (i) flexibility and (ii) efficiency. On the one hand, efficiency may be expressed by a variety of performance indicators, for example, lead time and variable cost. Efficient manufacturing processes are usually established by means of standardized designs and processes in collaboration with a high degree of automation. On the other hand, flexibility refers to organizational abilities related either to the manufacturing process (e.g., reacting quickly to demand changes) or to its outcome (e.g., offering a broad range of product variants). A trade-off exists between both dimensions, which makes it practically impossible to achieve maximum flexibility and maximum efficiency simultaneously. Manufacturing systems must consequently be optimized for one specific objective as the co-existence of job shop and flow shop production demonstrates. Here, the optimal design of real-world manufacturing systems is ultimately limited by the set of technologies that companies have at their disposal. The current state of technological skills and resources thus define a technology frontier which separates feasible production scenarios from the Star Trek Replicator and other fictional devices from the 'world of magic'. From a business perspective, the rise of AM extends this technology frontier along the flexibility axis and opens opportunities for manufacturing companies in three regards (see Figure 1):

1. First of all, AM offers the option of generating objects that would have been impossible to make with any other technology. This higher level of flexibility refers not only to the actual production outputs but also to tools, which can be prepared more easily (so-called 'rapid tooling').
2. In the context of job shop manufacturing, AM can be used as an automation technology which substitutes human labor. Though it may seem counterintuitive at first glance, the flexibility of 3D printers thus allows for efficiency gains.
3. Last not least, AM allows for cost-efficient switching from traditional mass production to new areas of mass customization. Here, companies use AM for the purpose of offering their customers a broader product range, individualized products, or shorter product life-cycles over time.

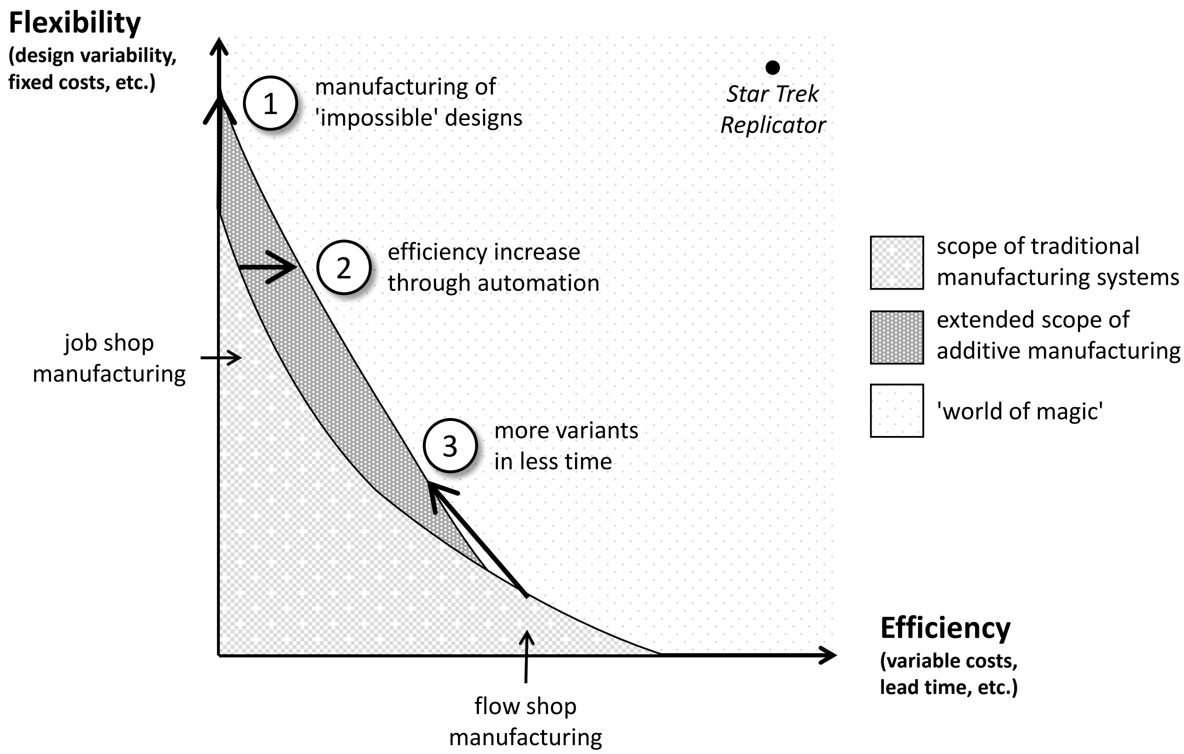

Figure 1 Impacts of 3D printing on manufacturing systems

Against this backdrop, it seems evident that the long-term impacts of 3D printing will not be limited to production processes but rather affect other parts of the value chain, for example, R&D, marketing, and logistics. In many of these cases, information systems will inevitably play a major role as the enabling or the supporting technology in an efficient execution of business processes, optimal product designs, and customer integration into the innovation process, among others. As a consequence, IT departments, software and IT service providers will sooner or later be confronted with a variety of challenges surrounding the management of 3D-printed goods and their digital counterparts. In order to discuss these issues, we have invited experts from different research institutions to present their views on Additive Manufacturing along the following questions:

- What could be the long-term economic impact of additive manufacturing on an organizational or industry level?
- How do you evaluate the current state of the technology and further necessary developments in the forthcoming years?
- Which recommendations could be given to managers today regarding the use of AM techniques?
- What might be a relevant contribution of management research – and IS research in particular – in this context?

The following researchers agreed to participate in the discussion (in the order of the following contributions):

- Prof. Dr. Hans-Georg Kemper, Michelle Moisa, Dominik Morar, Dr. Heiner Lasi, Chair of Information Systems I, University of Stuttgart
- Prof. Dr. Frank Piller, Technology & Innovation Management Group, RWTH Aachen University
- Prof. Dr. Peter Buxmann, Software Business & Information Management, Darmstadt University of Technology
- Dr. Letizia Mortara, Dr. Simon Ford, Dr. Tim Minshall, Centre for Technology Management, University of Cambridge

Hans-Georg Kemper, Michelle Moisa, Dominik Morar, and Heiner Lasi are all members of the Chair of Information Systems I at the University of Stuttgart. In their research and as part of the Working Group for Additive Manufacturing they focus on its industrial use and the several unique properties of AM compared to other manufacturing techniques. Beyond the technological potential, they also highlight economic as well as novel ecological opportunities. To benefit from all these aspects, a holistic view of the underlying creation of value is necessary, which involves core topic areas of IS research.

In contrast, Frank Piller from the Technology & Innovation Management Group at the RWTH Aachen University lays the focus on consumers. He points out that AM reduces the benefit of conventional economies of scale. In addition, AM fills the ‘missing link’ that is required for local manufacturing at the point of use. In his opinion, the lower entrance barriers to manufacturing capabilities will lead to user entrepreneurship that will largely influence the locus of innovation and production.

For Peter Buxmann from TU Darmstadt, the impact on economies, social life, entrepreneurship, and innovations is beyond dispute. Therefore, he discusses how fast and radically 3d printing will change the world. He argues that the maker movement is one vital part and a key driver of future digital fabrication systems, which provide interesting research opportunities, for instance, with regard to the impact on business processes and networks.

Letizia Mortara, Simon Ford, and Tim Minshall are all members of the Centre for Technology Management at the University of Cambridge. They consider not only the strengths and possibilities of AM but also focus on the differences between consumer and industrial AM. Because of the complexity of the topic, they propose a multidisciplinary research approach. According to their opinion, there are various promising domains for further research such as intellectual property issues, standardization, or product liability.

In sum, all contributors share the view that AM entails a variety of impacts that will most likely exert an influence on many different business processes within organizations and beyond. The corresponding managerial implications of 3D printing are poorly understood so far and still pose an unresolved question to both practitioners and researchers alike. Due to its cross-functional nature, the IS discipline is well-positioned to make a relevant contribution in this rapidly evolving thematic area.

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2 Additive manufacturing as an industrial manufacturing technique

The term Additive Manufacturing (AM) covers manufacturing techniques which produce physical products by applying material in layers. For this purpose, various technological alternatives exist. They range from printing liquefied polyamide on “desktop printers” to laser-sintering of ceramic material, which can for instance be found in aviation industry. These technologies are not new per se but have already been used for decades in the area of prototyping (Gebhardt 2013; Gibson et al 2014). However, technological advancements as well as new printable materials have led to an increasing distribution of 3D printing concerning the consumer sector on the one hand, and of Additive Manufacturing used in industrial production on the other hand.

Both areas overlap conceptually but differ entirely concerning technological and economical aspects. Therefore, in our opinion a strict division between the “consumer 3D printing” and the industrial AM – as Gartner has illustrated in his Hype Cycle since 2013 (Gartner 2013) – is essential. The chair of Information Systems I of the University of Stuttgart focuses on the industrial use of AM which will also be the focus of the article. Our department is involved in interdisciplinary cooperations, for example as a founding member of the working group Additive Manufacturing of the VDMA (Verband Deutscher Maschinen- und Anlagenbau e.V.).

In this context, it has to be asserted that these manufacturing technologies and concepts primarily refer to engineering. As a result, it is widely assumed that the use of AM marks a technological advancement on the shop floor. According to this view, conventional manufacturing machines will be replaced by AM-systems in order to produce small batch sizes of existing products more economically. There are various reasons why we do not share this opinion:

1. *Technological potential of AM.* The layer-based manufacturing process of AM enables a production of individually designable products to the greatest possible extent. Restrictions concerning the producibility no longer exist. Thus, functions can be integrated into the product design. This leads to entirely innovative approaches in product development and can be proven by looking at multifaceted examples: In robotics, robotic arms with bionically designed joints can be realized; in aviation industry, components with cavities to isolate and reduce material are developed; in turbine construction, internally cooled turbine blades are possible, etc. In our opinion, this technological potential leads to a paradigm shift regarding product development. This paradigm shift results in the increasing understanding of products as individual solutions which will open up a completely new quality of functional products. In turn, it can be deduced that the service share concerning the product development increases strongly and the value creation will be relocated into the early phases of product development.
2. *Economic potential of AM.* The tool-free manufacturing enables the production of individual parts and small batches without any set-up time concerning the resources. This ensures an elimination of temporal and monetary input in the construction and production of tools. Furthermore,

capital-intensive provision of specific production facilities and production specialists is reduced to a minimum. Thus, conventional manufacturing know-how loses a majority of its significance. As a consequence, manufacturing becomes independent of location, time and know-how. Instead of capital- and machine-intensive production locations, AM enables a service-oriented "Print on Demand" infrastructure. This results in the possibility of separating product development and production, leading to new business models that focus either on services within product development or on offering manufacturing resources.

3. *Ecological potential of AM.* The illustrated characteristics explicitly encompass that AM is able to make a considerable contribution in order to increase resource efficiency. For instance, material is only applied in those areas where it is required for its purposes. According to experts, material and weight savings of over 30% may be possible regarding components in aviation and automotive industries. In addition, logistics processes can be digitalized through location-independent manufacturing. Thus, the physical flow of material can be reduced significantly. This would initiate massive changes in the logistics industry which might, for example, lead to a substantial reduction of emissions.

The illustrated potentials of AM seem to suggest that industrial value creation faces considerable changes. Although this corresponds to our appraisal, we see a restricting factor in the fact that various technical products consist of multiple components which can only profit from AM to a certain degree. In this respect, only individual sectors and particular manufacturers of the components of complex systems face changes in the short term.

However, a different impression arises when looking at the medium- and long-term impacts: Traditional industry is defined by capital-intensive production processes in which the factor 'capital' plays a crucial role. This impedes market entrance for competitors, especially for new entrepreneurs. The holistic view of the potentials of AM leads to the conclusion that, in the future, product ideas will be realizable by new market participants without a great deal of capital. Thus, a "New Economy" effect can change the industry entirely. It is for example possible that start-ups launch complex products in digital form which can be manufactured globally by service providers via AM.

A requirement for the implementation of AM-based business models is the availability of fully developed AM techniques. Having been used a considerable time in prototyping, these already exist for several materials. Furthermore, considerable research and development efforts are made which primarily concern the technological area. This includes the improvement regarding the techniques, the development of new procedures as well as the extension of printable materials. Therefore, we can state that the current discussion of AM in research is strongly driven by technology. A look at practical experience clarifies: AM is in many cases perceived as a manufacturing technology and is frequently discussed by those responsible for the production in companies. This bottom-up approach leads to the perception in management that the value of AM is limited to production. From our point of view, this does not hold true. In fact, a holistic consideration of the value creation based on the specific business strategy is necessary in order to exploit the full benefits of AM. Then, business processes have to be implemented on the basis of this consideration.

We are convinced that there are many research areas in these contexts to which information systems can contribute a relevant and valuable input.

Here, various design objects – from the level of business models to individual application systems and their components – can be focused on.

The potentials of AM offer plenty of starting points for novel *business models*, partially in new business segments. It needs to be explored which new aspects of business models are influenced by AM and how companies can react accordingly. For an industrial enterprise with conventional manufacturing processes, for example, it is important to know which capabilities are necessary in order to apply AM successfully and to integrate it into existing infrastructures.

On the *business process* level, various consequences must be considered. This includes the aforementioned fragmentation of value creation steps: A company constructs functional product parts whereas the customer contributes the product design. The production is then carried out by a service provider. Currently, there is a lack of concepts to realize such scenarios enabling a consistent separation of the methodical, functional and data-related product design and product functions. Assuming that this is a prerequisite to involve customers efficiently in product development,this area is the one which foremost is in need of further research. Information systems can and should make a contribution here.

Since AM leads to changes in process and product structures, new requirements regarding operational *application systems* arise. For instance, ERP systems are often based on bills of material, and in consequence the same applies to the planning of the production program, the production process and the material requirements. A part produced by the sole use of AM – which is made in one piece without assembly – does not feature an extensive bill of material, but a base element (Lasi et al 2014). Due to these characteristics of AM, new functional requirements regarding application systems arise. So far, they are all inadequately analyzed.

According to our findings, it can be summarized that AM is meanwhile technologically developed to such an extent that economic and IT-based issues concerning its use in industrial production have priority. Therefore, information systems can make a major contribution where its typical topics are concerned.

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3 Additive manufacturing – from user innovation towards user manufacturing?

Technological innovation has frequently been shown to systematically change market structures. Additive manufacturing (AM), or, colloquially 3D printing, is such a disruptive technology (Berman 2012; Vance 2012). Economic analysis of AM still is scare and has predominantly focused on production costs or other company level aspects (e.g., Mellor et al. 2014; Petrovic et al. 2011; Ruffo and Haque 2007), but has neglected the study of AM's impact on customer welfare and market structure. In this essay, I want to discuss the economic effects of AM on the locus of innovation and production. In particular, I am interested in how AM may enable a more local production by users, supplementing the recent development of an upcoming infrastructure for innovative users and "makers".

3.1 Local manufacturing and 3D printing at home

A distinctive feature of AM is frequently emphasized in the popular press: its suitability to be placed locally next to potential users, up to the point of locating a 3D-printer in a user's home (Berman 2012; de Jong and de Bruijn 2013; Vance 2012). Physical products have usually been manufactured at a production site far from the location of the end user. For many products fixed costs in conventional production lead to economies of scale. Some products are also simply too difficult to produce or to assemble for a regular user, as there is a need for specific knowledge or tools which are costly to obtain. The downside of this way of producing is typically that the fit of the final product rarely is perfect. Some products are needed "right away", others are produced in a standard setting at the manufacturer's while users would prefer a variety. Moreover, some products require a try-on and rework, again resulting in disutility for the user.

If these disutilities overweigh the economies of scale in production, there is scope for local manufacturing at the point of use. One of the core characteristics of AM is that it dramatically reduces the benefit of conventional economies of scale. As a result, local manufacturing could become profitable. Anecdotic evidence supports this observation: The price of personal 3D printers has decreased several magnitudes within the last 5 years, leading to a growth in the installed base of this machinery of 300-500% annually (Wohlers 2012). In addition, an accessible local manufacturing infrastructure based on AM is gaining ground. Companies like TechShop provide local access to AM at a pay-by-use model, comparable to the "copy shop" around the corner.

3.2 User innovation and AM

Local production may be foremost attractive for innovative users. Past research has shown that users have been the originators of many industrial and consumer products (von Hippel 2005). Especially when markets are fast-paced or turbulent, these lead users become a major source of innovation. Recent developments in IT have lowered the cost for users to innovate: steady improvements in design capabilities that advances in computer hardware and software make possible; improved access to easy-to-use development software; and the growth of an increasingly richer innovation commons that allows individual users to combine and coordinate their innovation-related efforts via the internet. But there has been a "missing link" (Skinner, 1969) in user innovation: manufacturing. Many (lead) users lack the resources and capabilities to turn their inventions into "real" products beyond prototypes, i.e., products with the same properties as industrially manufactured goods. Hence, users often freely revealed their innovations to manufacturers (Harhoff et al. 2003), benefiting from the capabilities of the latter to produce the product in an industrial and stable quality. Manufactures, in turn, benefited from taking on this task in that they were able to sell these products also to other customers, hence providing a distribution channel for the user invention. For broader development of user innovations, however, this system relied on the availability and willingness of a manufacturer to take up a user innovation.

AM could change this process. Users can turn to advanced AM technologies to produce smaller series of products not only for their own use, but also for distribution and sales to other local users. User innovation then will be supplemented by user manufacturing, which I define as a user's ability to easily turn her design into a physical product, either for own consumption or for (local) distribution. By eliminating the cost for tooling (molds, cutters) and switching activities, AM allows for an economic manufacturing of low volume and of complex designs with little or no cost penalty. AM further enables to manufacture multiple functionality using a single process, including also secondary materials (such as electrical circuits), reducing the need for further assembly for a range of products. In addition, integrated functionality can replace the need for surface coatings and textures (Wohlers 2012). All these characteristics make AM a perfectly suited manufacturing technology for user manufacturers.

3.3 AM and user entrepreneurship

With this production capacity available, user manufacturers may turn into user entrepreneurs. Recent research found that innovating (lead) users frequently engage in commercializing their developments (Shah et al. 2012). Accordingly, the term user entrepreneurship has been defined as the commercialization of a new product and/or service by an individual or group of individuals who are also innovative users of that product and/or service (Shah and Tripsas 2007). User entrepreneurs experience a need in their life and develop a product or service to address this need, before founding the firm. As a result, user entrepreneurs are distinct from other types of entrepreneurs in that they have personal experience with the product or service that sparked innovative activity and in that they derive benefit through its use in addition to the financial benefit from commercialization.

The option for local production via AM will also benefit user entrepreneurs. First of all, the sheer opportunity to obtain access to a flexible manufacturing system without investing in high fixed cost may turn more lead users into user entrepreneurs. Once they have started to commercialize their products, local user entrepreneurs may have an advantage over established manufacturers as they obtain better local knowledge of customer demand, which allows them to design products closer to local needs. Especially in a situation where customer demand is heterogeneous and customers place a premium on products tailored exactly to their needs, local producers may have an advantage over established manufacturers of standard goods, despite the latters' cost advantages due to strong economies of scale. A system of entrepreneurial user manufacturers could have a major impact on the market structure in a given industry.

3.4 Conclusions

Concluding, I propose that AM will largely influence the locus of innovation and production. To achieve economies of scale, many physical products have previously been manufactured far from the site of end use. This can sometimes create high costs for the user due to the lags involved in acquiring something physical that is needed "right away" and "just as I like it". In these cases, AM of physical products at the point of use can make sense even if it comes with high production costs per unit. This market demand, in turn, induces development of on-site manufacturing methods and equipment. Once these are available, they tend to become progressively cheaper and to serve larger segments of the market.

However, the question whether production will shift to a system of local manufacturing is nontrivial: Firstly, under competition, existing manufacturers may react with pricing and/or product enhancements, increasing the appeal of their offerings. Secondly, it has been shown that the strive for economies of scale in a centralized conventional manufacturing system establishes a strong and very proven regime that is difficult to break up. Finally, the threshold to engage in manufacturing of their own may be high for many users. Consider the case of digital photo printing: After a strong rise of home photo printers, the market today is equally divided into decentralized printing kiosks in drugstores and large scale, centralized labs served via the internet. The printing of glossy photos at home, however, has strongly diminished. Whether these are transitional adaption effects or structural constraints, future research will have to show.

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4 The digital fabrication: impact on economy and society

The impact of the so-called Digital Fabrication on economies, social life, entrepreneurship, and innovation is without any doubt fundamental. Technologies like 3D printing, 3D scanning, or laser cutting enable the transformation from bits to physical objects and vice versa. Analysts have great hopes for Digital Fabrication. For example, McKinsey predicts that 3D printing will have an economic impact of 550 billion US-Dollar a year by 2025.

Thus, the real question is: How fast and how radically will these new technologies change the world? How will the upcoming change challenge the parties affected? Right now, Digital Fabrication empowers innovative individuals and enterprises to transform their ideas from a digital sketch into a physical object, i.e., individuals or enterprises can build prototypes within hours. At the same time, the Internet – and particular platforms like Thingiverse – allows sharing ideas with other individuals worldwide.

Active participants of the movement related to Digital Fabrication often call themselves “makers” (Anderson 2012). This “makers movement” consists of user innovators (van Hippel 1986) who use software tools to create digital designs and either turn them into physical products with the help of new technologies (e.g., 3D printers, laser cutters, or CNC tools) or have these produced by third parties (Anderson 2012). In addition, the makers movement also represents a culture as it is known from the “traditional Web 2.0 world”: Similar to open source projects, digital designs are often shared and then used or extended by third parties. This culture presents a key driver of innovation and might fundamentally change the way how physical products are designed and produced.

To obtain a deeper understanding of the developments in the field of Digital Fabrication and individuals’ willingness to share 3D-Objects, we implemented a crawler to gather information from the Thingiverse platform. Thingiverse is a website on which its members can share 3D models. Since these models are available under Creative Commons licenses, they can be downloaded, adopted, and printed, and many members collect their favorite models in public libraries. So far, about 100,000 3D models are available to users which has already led to a total of approximately 17,000,000 downloads from the platform. All in all, about 50,000 active users (i.e., users who do not just download models) belong to the community. These users have already written about 100,000 comments and created about 50,000 collections. The community is still growing.

One promising perspective is the observation of projects that develop at real and virtual meeting points of the maker community. Internet portals, relevant forums and blogs, maker spaces, hacker spaces, and fabrication laboratories (fablabs) are the locations where innovative technologies are used and where these projects are realized. Today is the perfect time to discover their potentials, also for the IS community.

At the same time, the 3D printing market is expanding and the price-performance ratio is substantially improving. The variety of printers is growing and 3D software developers are selling new programs and tools (or give them away for free). Furthermore, service providers enter the 3D printing market, for example Shapeways, Ponoko, or Sculpteo. As a result, a software ecosystem around Digital Fabrication is emerging.

Against this background, some interesting research opportunities are arising. Examples are:

- The impact of Digital Fabrication on innovation processes, and in particular user innovation
- The impact of Digital Fabrication on entrepreneurship and startups
- The analysis of open innovation approaches in the makers environment
- The impact of the makers movement on business formations
- The usage of Digital Fabrication within enterprises and their impact on logistics, value chains, etc.
- Comparisons between the maker movement and open source communities

Furthermore, a huge potential for changes has emerged through the advent of Digital Fabrication in the field of teaching (Buxmann/Hinz 2013): The establishment of maker spaces, hacker spaces, fablabs, etc. in universities and colleges might be a rule changer for students of different disciplines. Moreover, Digital Fabrication and decreasing prices for these technologies will also involve tremendous impacts on education. Parts of higher education as well as school schedules will change or have to change in the near future. Many technical internships at universities or manual training programs at schools will become more and more digitalized and thus completely differ from today's standards.

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5 3D printing enabled re-distributed manufacturing: a research agenda

5.1 Introduction

3D printing includes a broad range of technologies (Horn and Harrysson 2012) which offer the prospect for substantial industrial and manufacturing transformation (Petrick and Simpson 2013). The advocated advantages of these technologies include mass personalisation (Berman 2012), localised (Birtchnel and Urry 2013), flexible and agile (Vinodh et al. 2009) and sustainable production (Garrett 2014).

The envisioned societal and economic benefits for such a transformative manufacturing have attracted interests of the public, the press and policy makers. Many recognise the potential for reducing the footprint of manufacturing (e.g. manufacturing less goods, only when needed, closer to the point of consumption, repairing easily otherwise irreparable goods), the economic benefits for the industries who adopt these technologies (e.g. reducing inventories, using less material, relying on local labour), as well as for better potential for improving how individual customers' needs are served. One of the clearest examples of this last benefit lies in the possibility for local surgeries and hospitals to use 3D printing to provide personalised implants for individual patients. Adopting 3D printing in healthcare could reduce operation and recovery time and result in better outcome for patients, at potentially lower costs, ultimately benefitting the whole healthcare provision system.

The recent availability of these technologies for the wider public has been possible thanks to open source movements such as “RepRap”, which resulted in the availability of much lower cost 3D printing equipment (home 3D printers)[1] and their rapid diffusion amongst the general public[2]. Fabrication spaces (Fab-spaces) such as TechShop, Makerspaces or Fablabs are another means for the general public to access additive and other professional manufacturing technologies. Fab-spaces are the cultural cradle for the “Maker Movement” (Anderson 2012) whose philosophy is based on the joys of invention, knowledge sharing and experimentation. This ‘democratization of manufacturing technologies’ is thought to promote collaborative innovation and peer-production ecologies (Rigi 2013; Moilanen and Vadén 2013) with the potential of disrupting traditional supply chains (Waller and Fawcett 2014).

However, although constantly improving, current home 3D printers allow very elementary performance and do not yet provide a practical manufacturing route for the majority of products. At the same time, other technical issues do not yet allow the adoption of professional-grade 3D printing technologies for manufacturing in every condition or at an economically viable cost.

While the specific technical limitations in adopting 3D printing as a manufacturing process in industry remains the subject of research (Guo and Leu 2013), the potential impacts of the “re-distribution of manufacturing” through the implementation of these technologies in different industries have been widely anticipated (e.g. (Lyons 2012; Tuck et al. 2007)). This topic of re-distribution of manufacturing requires thorough scrutiny to evaluate their real feasibility and impact of additive manufacturing technologies adoption. A first step in identifying the key areas where further research is necessary has involved consultation with a broad community of stakeholders (researchers, industrial practitioners and policy makers) in the UK-Research Council-funded project “Bit by Bit. Capturing Value from the Digital Fabrication Revolution”[3].

5.2 A research agenda for 3D printing enabled re-distributed manufacturing

A review of the history of 3D printing (e.g. (Bourell et al. 2009) indicates how the study of these technologies’ relatively long emergence paths advance understanding of academic themes such as technology diffusion, technology adoption, technological change and disruptive innovation. For instance, recent research illustrates the importance of standards in the adoption and diffusion of emerging technologies and industries (O'Sullivan and Brevignon-Dodin 2012). Through studying the historical process of adoption of these technologies at the firm level, this topic could also provide fruitful learning on how technology management strategies could be implemented (Adner and Levinthal 2002) and how companies progressively assimilate signals of technological change through intelligence systems (Mortara et al. 2009).

The numerous and complex interconnections between technological, commercial and contextual aspects of technology diffusion can be mapped in order to highlight the emergence of the 3D printing industry and the adoption of the technology for different applications (Phaal et al. 2011). An exercise with mapping, focusing on the historical products and on the markets targeted by the current key additive manufacturing players[4],

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[1] http://3dprintingindustry.com/2014/08/13/crowdfunding-the-low-cost-desktop-3d-printer-part-6/
[2] http://3dprintingindustry.com/2014/08/14/consumer-3d-printing-serious-growth-phase-according-photizo-group/
[3] http://www.ifm.eng.cam.ac.uk/research/teg/digital-fabrication/
[4] http://capturingthevalue.wordpress.com/category/mapping/

shows an expansion of the technology applications from only prototyping and design, to tooling (including moulds) and eventually manufacturing of parts, a process that could be interpreted through the lenses of speciation and punctuated technological equilibrium (Adner and Levinthal 2002). But what will the future hold? If many anticipate that a new paradigm for manufacturing will lead to a radical transformation, based on the re-distribution of manufacturing (Garrett 2014), much should be done to understand how this transformation will occur and its implications.

Clearly, for an appreciation of the economic costs involved in an adoption of these technologies, further work should be done to compare advances in 3D Printing with established manufacturing technologies to assess these latter's competitive evolution in the face of disruption (the so-called "Sailing ship effect" (Mendonça 2013)). The analysis of the economics of 3D printing in comparison with other production technologies is a complex and multi-level task and goes beyond the evaluation of elements such as energy consumption, based on current operating conditions (Baumers, et al. 2013). For example, for direct manufacturing, there has been little analysis of the issue of landed cost structures (i.e. costs broken out by categories like transport, labour and materials). Research needs to explore the different products/sectors, and to investigate where the decision tipping points are, between manufacturing on a global scale (with economies of scale), versus the more localised economies of 'one' (Petrick and Simpson 2013) closer to the customer. The analysis needs to include elements such as oil price increases and the estimate of value of the new markets which could be generated via 3D Printing.

However, 3D Printing-enabled re-distributed manufacturing will depend on factors far beyond costs economics. Hence, embracing socio-technical perspectives will also be necessary, to anticipate the societal implications and drivers of these new means of fabrication. To this end, scholars have begun to apply forecasting tools and methodologies such as Science Fiction Prototype to anticipate trends and possible futures (Birtchnell and Urry 2013; Potstada and Zybura 2013), but there still is scant evidence and research available. This area calls for further multidisciplinary research and we propose the following areas for investigation:

- Intellectual property (IP) related issues may accelerate or hinder their role within the re- distribution of manufacturing (Bradshaw et al. 2010), and impacting on the way laws see the nature of ownership. Topics for exploration include the interplay between open-source and proprietary strategies for firms (Weinberg 2010), and the control of digitised content (e.g. Digital Rights Management of 3D design files, with parallels to the copyright issues faced by the entertainment industry). How will companies capture the competitive advantage and control value in the age of digital fabrication? What business-models will emerge which will allow companies to better protect and exploit IP?
- Product liability and quality assurance models. How will companies manage to protect themselves from liability and assure product safety? For instance, the mass customisation benefits of 3D Printing technologies mean that products are being made either as one-offs or in very low volumes (Piller 2007). What is the impact of this on the quality and validation processes? And, how can the quality of at-home/at-store produced spare parts, or the quality of at- pharmacy produced capsules be validated?

- With the advent of the re-distribution of manufacturing, the process by which standards have traditionally been enforced (O'Sullivan and Brevignon-Dodin 2012) might change and need to be re-invented. What standards need to be developed to enable design, production and quality assurance on a re-distributed manufacturing basis? Furthermore, how does the ecosystem of prosumers coalesce around particular standards?
- Also, the implied simplicity of 3D Printing processes masks a range of skills-related issues. Though the core technologies date back over 25 years, the rapid recent acceleration in their deployment is revealing the need for higher level and more widely diffused knowledge of, among others, process and quality control, process and material selection, and design software specific for 3D printing. There is also the observation that the visibility and availability of 3D Printing technologies in the education sector may be driving increased interest in engineering and manufacturing.
- The transformation of manufacturing paradigms could lead to major economic paradigm shifts (Rigi 2013), on the basis of new cultural ethos such as that of Hakers and Makers, with societal issues relating to the ethics of the adoption of such technologies, for example in the military context (Mattox 2013), or for the bioprinting of living organs and tissues.

It is our anticipation that, among other benefits, improving our knowledge of how the adoption of 3D printing is enabling re-distributed manufacturing and of how re-distributed manufacturing is providing opportunities for 3D printing, will allow policy makers to better target research support in the areas of higher impact and to help overcome barriers to their implementation. To achieve this understanding, substantial academic research is required and we believe these five research areas to be very promising domains for investigation.

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