The Emergence of Additive Manufacturing

Introduction to the Special Issue of Technological Forecasting and Social Change

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Additive manufacturing (AM), more popularly known as '3D printing', is believed by many commentators to be underpinning a new manufacturing revolution. AM encompasses a broad range of manufacturing process technologies that are emerging to offer the prospect of on-demand, mass personalisation, with more localised, flexible and sustainable production (Hutchings and Martin, 2012; Mortara, 2009; Despeisse and Ford, 2015). Its adoption and implementation could disrupt the organisation of manufacturing and the ways in which companies capture value.

In industry, AM is the accepted term, while '3D printing' is commonly used to denote those machines used primarily by home users. The terms are often used interchangeably and both refer to *"a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies"* (ASTM, 2012). AM is not just a single technology. Instead there are a multitude of different technologies, each at differing levels of technological maturity, offering the option of using different materials, with different quality outputs. Among many classifications of AM, the ASTM propose seven categories depending on how the layers are created: (1) vat photopolymerisation; (2) material jetting; (3) binder jetting; (4) material extrusion; (5) powder bed fusion; (6) sheet; and (7) directed energy deposition.

While its recent popularity in the media can give it the appearance of an overnight sensation, AM has existed in some form for over three decades. As its technical performance has improved, it has grown from its original rapid prototyping use as a design aid, to become a direct manufacturing technology with applications across a variety of industries. The reasons for its adoption lie in its advantages relative to traditional manufacturing processes. The additive nature of AM allows new design freedoms; its digital nature means that direct manufacturing from 3D models is possible; and its tool-free nature enables more flexible manufacturing. These advantages combine to mean that AM can be used to manufacture bespoke customised products on demand that are economically attractive relative to conventional mass production methods (Berman 2012; Chen et al., 2015; Huang et al., 2013; Petrick and Simpson 2013; Petrovic et al., 2011).

However, numerous challenges to achieving its full potential remain. While many of these stem from the relative immaturity of these technologies for manufacturing and the performance improvements necessary for it to begin to substitute traditional processes, there are other challenges and barriers inhibiting its adoption and diffusion. These include issues of standardisation, intellectual property, certification, skills and education (Berman 2012; Petrick and Simpson 2013; Petrovic et al., 2011). Furthermore, its adoption has significant implications for the configuration and sustainability of manufacturing, and it is essential that such issues be identified and remedied before they become barriers to the growth of the industry (Chen et al., 2015; Huang et al., 2013).

As an emerging direct manufacturing technology, AM has been adopted in certain niche markets for small production runs of high value, high complexity products (Scott, 2012). These include traditional craft sectors such as jewellery; medical applications where personalisation to the human body is highly advantageous; and the prestige automotive and aerospace sectors where structural components can be designed and produced with enhanced attributes (AM SIG, 2012; Lyons et al., 2012). In this latter application, a landmark moment for AM will soon be achieved when the GE LEAP engine enters production in 2016. After more than fifteen years of capability development, GE will launch an engine that includes radically redesigned fuel nozzles that take advantage of AM's design freedoms. Applying the technology creates a lighter engine that will deliver fuel savings, with reduced part complexity and greater durability. GE has bet on these technologies because it is now sure that reliability and safety will not be compromised. The range of applications is expected to grow rapidly as AM technologies improve and demonstrations such as the LEAP engine are made. This expectation is also leading to many nations developing explicit public technology strategies to help ensure that any barriers to the potential value capture from AM technologies are removed.

While researchers have made significant advances on the technical side of AM, our understanding of the socioeconomic consequences of AM's emergence lags behind. In setting out to produce this special issue, the questions we posed potential contributors sought to open up this domain to investigate the socioeconomic implications of this multi-purpose technology. A focus on the manufacturing landscape and the actors and interactions within the emerging AM ecosystem reflect the questions we have been asking ourselves as part of the 'Bit by Bit: Capturing the value from the digital fabrication revolution' project[*] (www.dfab.info).

1. How will additive manufacturing affect the manufacturing landscape?
2. What impacts could the diffusion of these technologies have on manufacturing firms?
3. How can firms become global leaders in this new age of digital manufacturing?

The contents of this special issue begin to answer these questions. There are a multitude of theoretical lenses and analytical perspectives that researchers can take to exploit this emerging phenomenon. It should come as no surprise then that there is great diversity represented in the selection of papers in this special issue, with contributors focusing on AM systems, organisations, business models, industries and supply chains as the units of analysis, and covering the consumer 3D printing, hearing aids, consumer goods and food sectors.

The Contents of this Special Issue

- The non-disruptive emergence of an ecosystem for 3D Printing — Insights from the hearing aid industry's transition 1989–2008 *Christian Sandström*
- Investigating the feasibility of supply chain-centric business models in 3D chocolate printing: A simulation study *Fu Jia, Xiaofeng Wang, Navonil Mustafee and Liang Hao*
- The complementarity of openness: How MakerBot leveraged Thingiverse in 3D printing *Joel West and George Kuk*
- Additive manufacturing for consumer-centric business models: Implications for supply chains in consumer goods manufacturing *Marcel Bogers, Ronen Hadar and Arne Bilberg*
- From rapid prototyping to home fabrication: How 3D printing is changing business model innovation *Thierry Rayna and Ludmila Striukova*
- An alignment approach for an industry in the making: DIGINOVA and the case of digital fabrication *Michael Potstada, Alireza Parandian, Douglas K.R. Robinson and Jan Zybura*
- The cost of additive manufacturing: machine productivity, economies of scale and technology-push *Martin Baumers, Phill Dickens, Chris Tuck and Richard Hague*

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Grand claims have been made about how AM will transform the global manufacturing system (A.T. Kearney, 2015; D'Aveni, 2015; Markillie, 2012). While AM can be considered as a direct substitute for traditional manufacturing processes, its current economic benefits primarily lie in the production of customised goods. In some organisations AM will be a direct substitute for existing manufacturing processes, while for others it will be complementary to existing production methods, or a means of market entry because of the way that it lowers the cost of small-scale customised production and enables market trials. The first case, organisations directly substituting AM for existing manufacturing processes, is considered by Sandström in his paper *"Adoption without Disruption - 3D Printing's impact on the Hearing Aid Industry"*. As an early adopter of AM, companies in the hearing aid industry experienced setbacks as they experimented with different technologies and approaches. Each of the major players was able to make the transition to AM. The benefits they felt were economic in that using AM reduced manufacturing costs and time, but not to the extent that it provided a radical shake-up of the industry.

While industrial activity builds on what has come before in terms of technologies, when new industries emerge based on novel technologies there is very often little existing structure. New ventures entering such industries face a barely populated landscape in which they must establish the value chains themselves. Then as the value chains become established, competition shifts towards specialisation and complementary offerings. The story of one of the key players in the emergence of the consumer 3D printing market, MakerBot Industries, is described by West and Kuk in *"The Complementarity of Openness: How MakerBot Leveraged Thingiverse in 3D Printing"*. Originating in the open source RepRap project, MakerBot was founded in January 2009 before later being acquired by Stratasys in June 2013. In their paper, West and Kuk discuss the strategic significance of "selective openness". While MakerBot's 3D printers began as open and hackable machines, they became increasingly more proprietary. Openness was retained through its online site for digital designs, Thingiverse, which continues to support the modification and hacking of design files uploaded by users through Creative Commons licenses.

Alongside the challenges that individual organisations face to build the business ecosystem there are also significant challenges of learning and coordinating with other actors in the ecosystem. While there is still significant variety being generated, the early exploration and experimentation phase gives way to another phase where experimentation is done with greater knowledge of the technical capabilities and market conditions. This is a point at which sufficient uncertainty has been reduced so that actors can make investments more efficiently and avoid costly mistakes. Knowledge exchanges occur through newly-formed industry associations, and policies and standards begin to be enacted that further help reduce uncertainty and steer resources along preferred paths. Potstada et al. describe an effort to develop coordination, the European Commission Framework Programme 7-funded Diginova consortium, in their paper *"An alignment approach for an industry in the making: Diginova and the case of Digital Fabrication"*. This consortium used a technology roadmapping approach to identify the most promising applications of digital fabrication technologies, the windows of opportunity for these, and their expected time to market. Additive manufacturing is one of four fabrication technologies identified by the consortium as most promising, alongside digital printing, printed electronics and human applications. The application of roadmapping provides a means through which expert stakeholders can gain intelligence on state-of-the-art technologies and market applications, obtain insights into future patterns of development, and begin to coordinate their strategies with other stakeholders.

As described earlier, a number of barriers exist to the wider application of AM. One of the principal barriers is cost, which is the central focus of the paper by Baumers et al., *"The cost of Additive Manufacturing: machine productivity, economies of scale and technology-push"*. Developing a production cost model for the manufacture of end-use metal parts sees them consider two different AM systems, Direct Metal Laser

Sintering (DMLS) and Electron Beam Melting (EBM). Their findings indicate that the purchase price of AM systems is not the most significant cost that need be considered, provided that AM deposition rates are sufficiently high for amortisation across production runs. Instead it is the operating costs that are of greater importance, with system productivity the principal cost driver in AM. Accordingly, improving deposition speed in combination with build volumes will deliver the greatest cost improvements. The signs of such improvements to system productivity lead the authors to believe that, contrary to popular belief, AM may not be at such a disadvantage in terms of economies of scale relative to traditional manufacturing processes.

The emergence of AM has significant implications for the business models of firms, both those that choose to adopt it and those that are impacted by its adoption by others. In this emerging industry, how does a new venture determine its business model? Such a question is considered in the context of the food industry by Jia et al. in their paper *"Investigating the Feasibility of Supply Chain-Centric Business Models in 3D Chocolate Printing: A Simulation Study"*. They use a modelling approach to evaluate the supply chain effects of chocolate manufacturers and retailers adopting an AM-based customisation strategy as part of their business models. Their model indicates that there could be a first-mover advantage in terms of strategic positioning and financial profitability to whichever applies the AM technology first.

When applied to rapid prototyping and rapid tooling, AM has provided cost benefits as it has enabled shorter design processes and more flexible manufacturing. However as Rayna and Striukova discuss in their paper *"From Rapid Prototyping to Home Fabrication: How 3D Printing is Changing Business Model Innovation"*, the application of AM for direct manufacturing and home fabrication will disrupt how value is created, delivered and captured. The authors describe how AM enables a rapid prototyping paradigm to be applied to the business model. Manufacturers using AM become more mobile and flexible in their value creation activities, being able to plan, design and test more rapidly. They also highlight the way in which AM allows the democratisation of manufacturing, pointing to the increased competition that will result from the rise of prosumers.

The topic of business models and prosumption is further considered by Bogers et al., this time in the case of an established consumer goods company, in their paper *"Business models for additive manufacturing: exploring digital technologies, consumer roles, and supply chains"*. They focus on how integrating AM into the company's business activities can affect customer involvement, along with its implications on the organisation of the supply chain. They clarify how the use of AM shifts value-adding activity from the manufacturer to the consumer, as it allows customisation and co-creation to occur. As a consequence, they propose that a consumer-centric business model in which AM is used can be complementary to traditional manufacturing-centric business models. Furthermore, the adoption of consumer-centric business models can lead to more decentralised supply chains. This can occur as online platforms providing access to digital design files allow the consumer to download, personalise and manufacture the products and components in their home or office.

Implications of the Special Issue and areas for future research

The core themes addressed by these seven papers reflect key gaps in knowledge relating to the emergence and diffusion of AM technologies, i.e. the challenge of integrating AM into existing industrial systems versus the challenges of applying AM to create new industrial systems; the strategies that should be adopted by existing firms and new entrants seeking to create and capture value from AM technologies; broad issues of business strategy and specific technical challenges.

Phaal et al.'s (2011) framework for mapping industrial emergence provides a useful means through which we can classify the papers in this special issue and aids the identification of knowledge gaps. The content of the papers in this special issue primarily falls in the value capture and context categories. Those papers within the value capture category have analysed business models (Bogers et al.; Jia et al.; Rayna and Striukova; West and Kuk), sales and marketing (Jia et al.), supply network (Bogers et al.), and operations (Baumers et al; Bogers et al.). Meanwhile papers considering the value context have covered Government policy and regulations and standards (Potsdada et al.) and industrial dynamics (Sandström).

Though each paper provides a valuable step forward, this is still very much the tip of the iceberg in research terms and numerous gaps in knowledge remain. Further research is needed to continue exploring how AM is changing industries, the economy and society. Hence, drawing on these SI papers and our own insights, Table 1 uses the categorisation of Phaal et al.'s framework to propose research questions that should be investigated in this domain.

Category	Sub-categories	Potential research questions
Value context	Market trends & drivers	What are the effects of AM on global manufacturing systems? What are the implications of AM on industrial sustainability? How does the emergence of AM intersect with other political, economic, social, technological, legal and environmental?
	Government policy	What types of public policy are effective at supporting the emergence of AM? What policies are necessary to ensure that sufficient AM skills are acquired within the workforce? How can the distributed nature of AM support regional regeneration?
	Regulations & standards	How is the transition being made to the 3MF file format? How are proprietary and open material standards affecting AM adoption? How are quality standards defined and upheld in a distributed AM landscape? Who has liability for AM-produced goods?
	Industrial dynamics & competition	Who are the actors that are creating and capturing value and where in the AM ecosystem are they doing so? When and how have new entrants disrupted established industries through AM? In what circumstances have established companies maintained their competitive position through AM?
	Customers	How is AM enabling greater customer involvement in the manufacturing process? What are the different characteristics of AM prosumers and how are such prosumers using AM?
Value capture	Business models & strategies	What types of business models are being adopted in the AM ecosystem and which of these are proving more successful? When and how does AM enable product-service business models? How are companies responding to intellectual property rights disputes caused by AM? Under what circumstances does AM lower the barrier to market entry?
	Applications, product & services	What new products and services will be possible through AM? How have been/is being /will be customisation and personalisation applied through AM?
	Support services	How can AM be used for maintenance, repair, spare part and remanufacturing activities? How can the use of AM extend the life of products and components?
	Sales & marketing	What are customer perceptions of AM and how are they changing? Where in the hype cycle are different categories of AM? What price premiums can be achieved through the use of AM for personalisation?
	Distribution	How is AM changing mechanisms of distribution? How are retailers incorporating AM applications into their business models? How are online AM platforms and communities evolving?

	Operations	What are the challenges to integrating AM into existing operations? How is the automation of AM improving its cost efficiency? How is AM being integrated into hybrid manufacturing systems?
	Supply networks	How is the application of AM changing the structure and complexity of supply networks? What types of suppliers are being disintermediated through the application of AM?
Value creation	Design	What is design for AM and how can it be integrated with other design principles? What types of applications are being redesigned to take advantage of AM design freedoms and why? How are designers' attitudes to AM changing?
	R&D	How are engineers developing understanding of AM principles? What factors determine whether companies should make or buy AM components and products? What effect will a greater understanding of material properties and the development of new materials have on the adoption of AM?
	Management	What processes should companies use to certify AM components in specific sectors? Why are some organisations making the transition to AM and not others?
	Relationships	How is the adoption of AM changing the constellation of relationships within industrial ecosystems? How is trust established in a distributed AM landscape?
	Resources	What skills are needed to effectively use AM and how are they being acquired? How successful have crowdfunding-backed 3D printing companies been?

Table 1. Potential research questions relating to additive manufacturing

The papers in this special issue also provide useful illustrations of the range of methodologies that can be used to address the remaining gaps, from historical analysis, to cost modelling and simulation. Developing a richer understanding of the multiple and interconnected issues affecting the on-going emergence and diffusion of AM technologies requires a diverse portfolio of research tools, and these papers will hopefully stimulate further research using a range of such tools.

Overall it is our hope that the papers in this special issue provide a useful contribution to this nascent area and that other researchers will be inspired to conduct studies of their own. The topics and sectors covered in this special issue are just a small sample of those that are open for investigation. As our proposed questions indicate, there are many exciting opportunities for academic research in this area, as AM technologies, its applications and ecosystem emerge in real-time.

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