Guest editorial

Is additive manufacturing evolving into a mainstream manufacturing technology? Introduction to the special issue

Additive manufacturing is seen as a range of technologies with the potential to fundamentally change the way manufacturing is organized (Ford *et al.*, 2016; Hyman, 2011; Merrill, 2014; Sung-Won, 2013). Additive manufacturing technologies build up an object layer by layer. The American Society for Testing and Materials distinguishes seven categories of additive manufacturing technologies depending on how these layers are created (ASTM, 2012; Wohlers and Caffrey, 2013). In contrast, subtractive technologies, such as drilling and milling, remove material when making an object. Additive manufacturing technologies are generally more efficient than subtractive technologies in terms of material use. Oettmeier and Hofmann (2016) describe that additive manufacturing technologies apply the same principle: based on a digital blueprint, materials are joined to form 3D objects. As a result of this principle, the manufacturing process becomes more flexible, in terms of batch size and adaptation of objects, than injection moulding and casting technologies. The latter manufacturing technologies use expensive moulds that require large batch sizes to make the manufacturing process cost-effective.

Two special issues are formed to create a vision on the impact of additive manufacturing. The first issue was published in December 2016 in the *Journal of Manufacturing Technology Management*, the second issue is introduced now. Both special issues aim to understand the history of the emergence of additive manufacturing, to analyse current technical and market developments and to explore future consequences of this technology for the structure of manufacturing industries and the economy at large. Before summarizing the contents of the papers in this second special issue, we would like to describe some of the notions that emerged from the first issue (see also Ortt, 2016).

Notions from the first special issue (December 2016)

A potential to disrupt entire industries but an introduction in niche markets only

In our first special issue on additive manufacturing an interesting phenomenon can be witnessed. On the one hand, several articles in this issue convincingly claim that additive manufacturing will fundamentally restructure existing industries. On the other hand, articles in the same issue also reveal that additive manufacturing is mainly adopted in niche markets. Niche markets are defined to comprise a relatively small group of customers with specific wants and demands regarding a product (Dalgic and Leeuw, 1994; Shani and Chalasani, 1993).

Several articles in the first special issue describe that additive manufacturing technology has the potential to restructure existing industries. Kothman and Faber (2016) describe the potentially disruptive changes of additive manufacturing in the construction industry. Oettmeier and Hofmann (2016) describe that additive manufacturing requires a significant redesign of the external supply chain structure around a company and the internal processes within a company. Steenhuis and Pretorius (2016) explore the potentially disruptive effect of additive manufacturing in the consumer market.

While these articles indicate that the potential impact of additive manufacturing can be large and disruptive in a variety of manufacturing industries, articles in the same special issue also show that the application of additive manufacturing is confined to niche applications. Meisel *et al.* (2016), for example, focus on particular niche applications for additive manufacturing, the production of parts in remote or austere environments. Knofius *et al.* (2016)

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also describe a particular niche application: after sales service logistics in high-tech industries. Oettmeier and Hofmann (2016) focus on the effect of additive manufacturing in an engineer-to-order environment, in particular the hearing aid industry. Finally, Rylands *et al.* (2016) describe how manufacturing processes in two companies were complemented rather than substituted by additive manufacturing technologies. So, in none of these cases additive manufacturing was completely substituting traditional manufacturing technologies in a mainstream market.

Apparently, additive manufacturing is a disruptive technology that, irrespective of its predicted potential, is only diffusing in niche applications. Such a phenomenon is neither new nor unique. Scholars from diverse disciplines have observed that many radically new technologies need a long period of time before large-scale diffusion starts (e.g. Mansfield, 1968; Utterback and Brown, 1972). Agarwal and Bayus (2002) found an average period of 28 years between invention and commercialization for 30 breakthrough innovations from diverse industries. A similar period was found by Ortt (2010) who tracked the time between invention and large-scale diffusion of 50 radically new high-tech products and systems. Several authors describe a generic pattern of development and diffusion (Kemp *et al.*, 1998; Ortt and Schoormans, 2004; Tushman and Rosenkopf, 1992) in which large-scale diffusion is preceded by multiple niche applications. It seems as if the niche applications demarcate a transition period (Kemp *et al.*, 1998) from an emerging technology towards a mature technology.

For additive manufacturing, several barriers seem to prevent direct large-scale diffusion. The costs of the emerging technology was initially high, and both the performance and user friendliness of additive manufacturing appliances were low (Ortt, 2016). In some market niches, however, the new additive manufacturing technologies were already cost-effective from the beginning on. In specific market niches, such as the market for hearing aids (Oettmeier and Hofmann, 2016), the market for dedicated parts in remote or austere environments (Meisel *et al.*, 2016), or the market for after sales service logistics in high-tech industries (Knofius *et al.*, 2016), additive manufacturing technologies provided unique benefits that made companies overcome the initial hurdles of low performance, high cost and lack of user friendliness. These market niches can be seen as the precursors of a transitions towards large-scale diffusion (Kemp *et al.*, 1998; Schot and Geels, 2008).

Practical and scientific implications of the emerging nature of additive manufacturing

In our first special issue on additive manufacturing the emerging nature of the additive manufacturing technology is reflected in two ways: the practical results obtained in the articles, and the scientific methodologies adopted in these articles.

From a practical and managerial perspective, the newness and versatility of technologies create a need for decision support to decide how and when to apply this technology. Decision support is offered by two articles in the first special issue. Meisel *et al.* (2016) describe that many types of additive manufacturing technologies exist, each of which can be applied in specific use contexts and with specific materials. Decision support is highly valuable in such a situation. Knofius *et al.* (2016) also offer decision support.

From a scientific and methodological perspective, the emerging nature of additive manufacturing technologies is reflected in the exploratory nature of methodologies adopted by authors of papers in our first special issue. Most of the authors adopted an exploratory approach, mostly case-studies describing a singular case or a limited number of cases in one industry only.

A next step: the contents of the second special issue

After the more exploratory and case-based approaches described in the first special issue, we will now take a new step in our exploration of additive manufacturing technologies.

One article in this issue will report a systematic literature analysis on additive manufacturing, another will provide an overall picture of the developments in additive manufacturing across countries all over the world. In contrast to several articles in the previous special issue, where singular cases were explored, in this issue articles will explore multiple cases to derive systematic relationships and contingencies. Finally, articles in this issue will explore strategies or business models that practitioners can adopt in their efforts to create a mainstream market for additive manufacturing. Below we will summarize and introduce the seven articles in this special issue, starting with a practitioner view of one of the pioneers in the field.

Ian Gibson (2017) in the first article with the title "The changing face of additive manufacturing" (p. 10) describes that 3D printing machines were, at first about 25 years ago, slow, inaccurate, difficult to use and expensive. Gibson starts his article by capturing the essence of what additive manufacturing actually is, and why it is so important to product developers and manufacturers. The article then proceeds with an analysis of the major industry sectors. Finally, the discussion explores where the technology is leading us and where the major research pushes this exciting technological field.

The authors of the second article (Jin *et al.*, 2017) with the title "A scientometric review of hotspots and emerging trends on additive manufacturing" (p. 18) use a systematic literature analysis to indicate emerging trends in additive manufacturing. In doing so they explore new technological developments and they compare additive manufacturing research fields. The paper visualizes the intellectual landscapes of additive manufacturing and identifies where new additive manufacturing research can be witnessed.

The authors of the third article (Bai *et al.*, 2017) with the title "The pattern of technological accumulation: the comparative advantage and relative impact of China in 3D printing technology" (p. 39) use a systematic patent analysis to track developments in additive manufacturing across countries. The authors show that China, the USA, Japan and Germany are the leading countries in 3D printing technology while the patterns of technology accumulation in these countries are fundamentally different. The article explores some other countries where fast growing technology subfields can be witnessed.

The fourth article (Khorram Niaki and Nonino, 2017) has the title "Impact of additive manufacturing on business competitiveness: a multiple case study" (p. 56). This paper identifies the impacts of additive manufacturing on business performance. The authors aim to determine the contingent factors driving performance by adopting a multiple case research methodology with a sample of 16 heterogeneous companies. The findings reveal, for example, how the implementation of additive manufacturing in rapid manufacturing metal products has boosted productivity.

The authors of the fifth article (Holzmann *et al.*, 2017) with the title "User entrepreneur business models in 3D printing" (p. 75) explore how users of additive manufacturing technology adopt specific business models and become suppliers of additive manufacturing services. In the article, data from eight user entrepreneurs are analysed, applying qualitative content analysis. The results indicate that user entrepreneurs focus primarily on the combination of low opportunity exploitation cost and a large number of potential customers.

The sixth article (Deradjat and Minshall, 2017) with the title "Implementation of rapid manufacturing for mass customisation" (p. 95) draws upon the experiences of firms in the dental sector to indicate how additive manufacturing can be used for mass customisation. The article adopts a multiple case-study approach using six companies and reports how these companies implemented additive manufacturing technologies to create mass customization. The results show the type of considerations and challenges that companies face in the process of implementing additive manufacturing technologies. These considerations and challenges are shown to depend on the stage of implementation and the maturity of the specific additive manufacturing technologies.

In the seventh and last article, with the title "The additive manufacturing innovation: a range of implications" (p. 122), Steenhuis and Pretorius (2017) explore differences in additive manufacturing technology implications across industries. Using a desk research approach, they conclude that the degree impact of additive manufacturing depends on the industrial sector involved. Additive manufacturing can be seen as an incremental innovation in one industry, while it is a radical innovation in another industry. The authors claim that developments in additive manufacturing not only revolutionize specific industries but can also cause fundamental shifts in society.

Is additive manufacturing evolving in a mainstream manufacturing technology?

In the first special issue it was described that additive manufacturing technology is primarily used in niche applications next to, or complementary to mainstream manufacturing technologies. It was also shown that additive manufacturing has the potential to substitute these mainstream technologies and thereby disrupt traditional markets for manufacturing goods. This second special issue therefore poses the question whether additive manufacturing technology is about to become a mainstream manufacturing technology. How can the shift from an emerging technology to a mature technology be assessed or even previewed? We will start with discussing the literature that addresses this generic question and we will search for variables that this literature proposes to preview an upcoming shift of an emerging technology from niche markets to mainstream markets. These variables will then be applied for the case of additive manufacturing.

A generic pattern of development and diffusion of emerging technologies

In the past several authors have addressed the generic question how to assess or preview the shift of an emerging technology applied in niche markets to a mature technology applied in a mainstream market. These authors envision different types of patterns for the development and diffusion of technological products, each of which has distinct phases (e.g. Agarwal and Bayus, 2002; Moore, 2002, Ortt and Schoormans, 2004; Rogers, 2003; Tushman and Rosenkopf, 1992). In general, after the invention of a new technological principle, three phases can be distinguished Ortt and Schoormans, 2004; Ortt 2010). The first phase lasts from the invention of the technological principle up to the first introduction of a product version incorporating that principle. After the introduction, instead of a smooth start of a diffusion process that gradually gains momentum, most often an erratic process of diffusion of different product version in multiple market niches can be witnessed. The second phase is therefore seen as the time from the first introduction up to the start of large-scale production and diffusion of a kind of standard product in a mainstream market. The third phase lasts from the start of large-scale production and diffusion to the end of the product life cycle.

How to preview a shift of an emerging technology from niche to mainstream market

If we apply this model of development and diffusion to additive manufacturing technology then it is obvious that the technology has already moved from the first to the second phase. The question is whether the technology is about to move to the third phase, i.e., from niche applications to a mainstream application. To answer this question we will go back to the authors envisioning a pattern of development and diffusion and explore what the mechanism are that drive the pattern and hence the phase transition from niche markets towards a mainstream market. Some of these authors reveal indicators allowing us to see where additive manufacturing technology stands.

Summary of indicators in the literature

A first group of authors focuses on the supply side of the market and indicates the maturity of the technology in terms of reliability and performance. Mankins (1995, 2009) was working at NASA and proposed a tool to indicate the level of maturity of different technologies in order to track the progress in technology development of various subsystems. We will use performance and reliability aspects to track whether additive manufacturing technology can be used on a large scale.

A second group of authors focus on the demand side of the market and distinguishes typical characteristics of subsequent adopter groups. Rogers (2003), for example, distinguishes between innovators, early adopters, early majority, late majority and laggards. In hindsight, these groups can be distinguished but a review of typical characteristics of such groups reveals that such generalization do not hold across product categories and are not consistently found by different authors investigating the same product categories (see e.g. Engel *et al.*, 1990, p. 710). Moore, therefore, broadens Rogers' perspective by distinguishing typical subsequent customer groups and the typical business model or marketing mix for these groups. Moore's first groups of adopters are the technology enthusiasts and the technology visionaries. Technology enthusiasts like to experiment with new technology, such as the first hobbyists that build their own 3D-printer. Technology visionaries adopt the technologies in their company because they have a vision how this technology will entirely change the organization. Both groups of adopters typically represent niche markets. In contrast, the early majority or pragmatists are customers that demand a product that is adopted by and supplied by reputable companies. They demand a product including all complementary products and services, that is easy to use. Adoption by this group typically coincides with the start of large-scale production and diffusion. We will use the characteristics of the type of product that they demand as an indicator for the upcoming phase transition.

A third group of authors look at the interaction of market actors and the indicators of an upcoming shift towards large-scale diffusion. Agarwal and Bayus (2002), for example, observed that before the start of large-scale diffusion, prices of equipment drop.

In Table I, indicators as suggested by the three groups of authors are used to explore whether additive manufacturing technology is about to enter a phase transition towards large-scale production of standard products.

The conclusion from Table I is that additive manufacturing technologies are still scarcely applied by manufacturing companies to produce standard products on a large-scale. Performance and reliability, ease-of-use and user-friendliness still need to be improved. However, the complementary products and services, including education of engineers and even kids on primary schools, 3D-design software and so on, are all widely available. Business models to apply additive manufacturing technologies on a larger scale are known and the price of additive manufacturing technologies is rapidly dropping. As a result, the first companies decided to adopt additive manufacturing for large-scale production of specific parts. Gibson (2017) sees a host of AM technologies, some of which are at a relatively early stage and some at an almost mature stage. We conclude that additive manufacturing is starting to shift from niche applications to a mainstream market.

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Grp.	Indicators of phase transition (source)	Data for additive manufacturing (source)
1	Reliability and performance issues in AM equipment (Mankins, 1995, 2009)	Gibson (2017) describes that it is difficult to maintain an acceptable accuracy or surface finish. Furthermore, metal AM results in mechanical properties that are too variable for many aerospace applications Deradjat and Minshall (2017) claim that several performance and process barriers for large-scale use of AM still exist, such as insufficient material properties and difficulties with material removal Steenhuis and Pretorius (2017) describe that, in the construction industry, the reliability, safety, sustainability aspects of additively manufactured houses has not yet been established
2	Availability of easy to use AM equipment or products (Moore, 2002)	Steenhuis and Pretorius (2016) indicate that AM equipment still lack in terms of ease-of-use and user-friendliness
	Availability of complementary products and services required for AM (Moore, 2002)	Gibson (2017) indicates that: 1. Availability of computer-aided-design (CAD) for 3D modelling helps diffusion of additive manufacturing equipment 2. Alternative technologies have converged in such way that they are all make use of digital 3D model data and can be integrated in conjunction with the internet 3. Recent developments in photogrammetry technology, which in turn has been enhanced by advanced camera technology, have simplified the process of acquiring high quality 3D surface and measurement data Steenhuis and Pretorius (2017) indicate how using AM-technology has become a part of job requirements for many engineers and how the technology has entered the school and education system
	Creation of AM business models to enter mainstream market Moore (2002)	Deradjat and Minshall (2017) show how AM can be used for mass customization. This would be a model that allows large-scale diffusion. The data, however, is drawn from the niche market of dental care
	Large well-known manufacturers use AM to produce standard products on a large scale (Moore, 2002)	Gibson (2017) describes that GE started to use AM to manufacture parts, fuel nozzles, for jet-engines on a large scale (see also www.geaviation.com/commercial/engines/) PWC estimated in 2014 that about 10% of the manufacturing companies were using AM for prototyping and production, 0.9% was using it for production alone (www.forbes.com/sites/louiscolumbus/2015/03/31/2015-roundup-of-3d-printing-market-forecasts-and-estimates/#63381ae31dc6)
3	Prices of 3d-printer go down Agarwal and Bayus (2002)	Gibson (2017) describes that key patents for the fused deposition modelling technology owned by Stratasys lapsed and that created a pricing war that reduced machine costs. Machines are now so affordable that many people have machines at home In contrast Deradjat and Minshall (2017) still see several financial barriers for large-scale adoption and use of AM: high capital investment, high material and maintenance costs, and high process costs Steenhuis and Pretorius (2017) describe that AM-systems are already competitive for volumes up to 10,000 units

Table I.
Indicators of upcoming large-scale diffusion

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