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The magic cube: towards a theoretical framework to explain the disruptive potential of additive manufacturing

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Abstract

Additive manufacturing (AM) is an umbrella term for various layer-based manufacturing processes which are often portrayed as a new technological revolution. Despite impressive AM process developments the revenue of the AM industry is still a fraction of that of other manufacturing processes. This AM based revenue discrepancy raises many questions. They include: (1) What makes AM so special? and (2) How could the disruptive potential of AM be unlocked? We seek to add to the literature by providing an answer to elements of these questions through the development of a framework we call the 'Magic Cube'. We utilize the concept of vertical and horizontal innovation theory as one basis for this framework. Further we adopt a tension perspective on automation and individualisation drawn from operations research to develop a theoretical framework. The result is the 'Magic Cube', a tool that is designed to support researchers and practitioners in demonstrating the unique strengths of AM and its potential areas of application.

Introduction

Additive manufacturing (AM)—also referred to as 3D printing—is a layer-based manufacturing process. It is described as, 'joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining' (ASTM International 2012). AM is still often regarded as 'the next major technological revolution' (Rayna and Striukova 2016, 214) even after some 30 years of application. The use of AM is growing with a two-digit year-on-year growth and a market revenue in 2016 amounted to only $6.063 billion (Wohlers Report 2017). Yet this is a marginal amount compared to the global smart manufacturing market of $ 172.34 billion in 2016 (Grand View Research 2017). The average successful disruptive technology gains market acceptance in under 20 years (Linton and Walsh 2008, Yanez *et al* 2010).

Possible explanations for the slow adoption rate of AM are (1) technical limitations such as slow production times and unsuitable machinery (Bonnín-Roca *et al* 2017), (2) economic limitations like high initial machine and material costs (Jiang *et al* 2017) and (3) organisational shortcomings such as a general lack of appropriate business models and a qualified workforce (Cautela *et al* 2014, Fink *et al* 2013) and also (4) design-related shortcomings (Tang *et al* 2016). Contrary to media reports, the current economic impact of AM is much smaller than assumed and the complexity of AM technology is often underestimated (Gartner *et al* 2015, Bonnín-Roca *et al* 2017).

Literature review

One common misunderstanding that contributes to the confusion concerning AM is that it is a single technology. In fact, AM encompasses a whole manufacturing paradigm and a wide range of different processes and techniques, including vat photopolymerization, material jetting, binder jetting, material extrusion, powder bed fusion, sheet lamination, and directed energy deposition (ASTM International 2012). Furthermore, while other manufacturing technologies like injection moulding usually handle one type of material (typically polymers), AM machines can process a wide range of materials from polymers, metals, and ceramics to concrete, food, and even living cells (Achillas *et al* 2017). Successful AM application therefore is a process of selection. A selection based on a balanced interplay of processing method (machinery) and material properties (material science) more so than any other manufacturing technique (Gatto *et al* 2015). When AM applications are successful it is often important to develop simultaneous expertise in diverse opportunity areas. This has been pointed out by other authors in application areas such as medicine (Marinakis *et al* 2017), tooling, and the aerospace and automotive sectors (Gartner *et al* 2015). Insufficient focus on one aspect can often cause an application of AM to be economically unsuccessful, leading not only to frustration but also to unfulfilled potential and financial losses (Maresch *et al* 2016, Maresch and Gartner 2017).

Previous research presents detailed case studies of special business cases, applications, and materials in an attempt to address the issue of the untapped potential of AM (Roach and Gardner 2017), alternative research has also examined issues of design and algorithm research (Tang *et al* 2016). However, these case studies often illustrate the potentials and weaknesses of only a single area of application. The limited generalizability of the resulting insights means they cannot be transferred across the diverse and heterogeneous arenas relevant to AM, and therefore the knowledge on the topic is rather fragmented.

Our research adds to the literature by adopting an integrative approach (Islam *et al* 2018), which makes it possible to identify the multidisciplinary and inter-industrial characteristics and dependencies inherent in all AM applications. Its aim is to contribute to the integration of this field of research by developing a theoretical framework that helps to explain the specific characteristics of AM and its cross-industry potential. For that, we apply the concept of vertical and horizontal innovation (the innovation perspective) and complement it with the idea of tension between automation and individualisation (the manufacturing perspective) and also with a cross-industry perspective.

The framework presented here provides an integrative concept of the disruptive potential of AM that not only contributes to the development of this field of research, but also provides important insights into the interdisciplinary challenges for the application of AM in practice. The framework reveals that the complexity of this production paradigm has been underestimated, which explains why AM has often not had the impact expected of it.

Tool development: the magic cube

First dimension—innovation perspective

Literature on research and development distinguishes between vertical and horizontal innovations. Vertical innovation encompasses improvements in quality or the creation of new knowledge within a certain discipline. Horizontal innovation involves an aim to create something new, by combining existing knowledge from different disciplines. Specialisation (vertical innovation) is based on the concept of the division of labour, and is widespread in both the workplace and in other areas of society (Connolly and Peretto 2003, Cozzi and Spinesi 2006). While specialisation is certainly responsible for considerable progress in research, business, and society, it can also lead to knowledge silos that lack practical impact. Innovative entrepreneurs sometimes create new market offers by accessing such knowledge silos and combining their content. To do so, they usually need an understanding of more than one discipline (or knowledge silo) or an ability to manage the interface between the knowledge on two areas of expertise (Goh 2002, Schneckenberg 2015, Krylova *et al* 2016, Forsten-Astikainen *et al* 2017), which is horizontal innovation. Only occasionally does any individual master more than one discipline, and polymaths like Leonardo da Vinci (who was a scientist, an engineer, and an artist) can have a significant impact on society for centuries (Isaacson 2017).

Vertical and horizontal innovation can be shown graphically on two axes—the x axis for horizontal innovations and the y axis for vertical innovations (see figure 1). The combination of both modes of innovation can be illustrated by spanning a polymathic or multidisciplinary matrix between the two axes. This matrix depicts the multidisciplinary nature of AM. The best AM machine or process is useless when the material properties cannot meet the stated needs and vice-versa (Roach and Gardner 2017). A strong interplay between processing techniques and material science is necessary to harvest the potential of AM.

Second dimension—manufacturing perspective

The manufacturing strategy of specialisation led to mass-manufacturing technologies like injection moulding that permit the efficient production of similar high-quality products in bulk (Eyers and Dotchev 2010, Achillas *et al* 2017, Deradjat and Minshall 2017). Specialisation often requires major investments in machinery but entails rather limited flexibility. We illustrate the dimension of specialisation on the y axis in figure 2. Artful craftsmanship, in contrast, fosters the production of highly individualised and often artfully-created high-quality products using individual tools. We illustrate the level of specialisation on the x axis in figure 2. Craftsmanship, based on manual labour, has less potential to tap into economies of scale; and accordingly very individualised manufacturing processes usually incur high production costs, and are accompanied by productivity constraints.

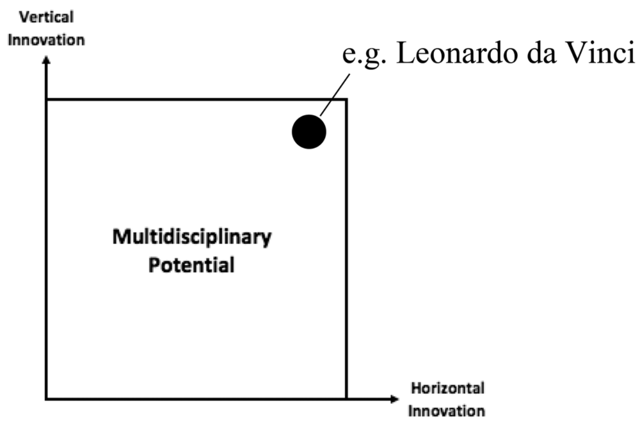

Figure 1. AM matrix from the innovation perspective.

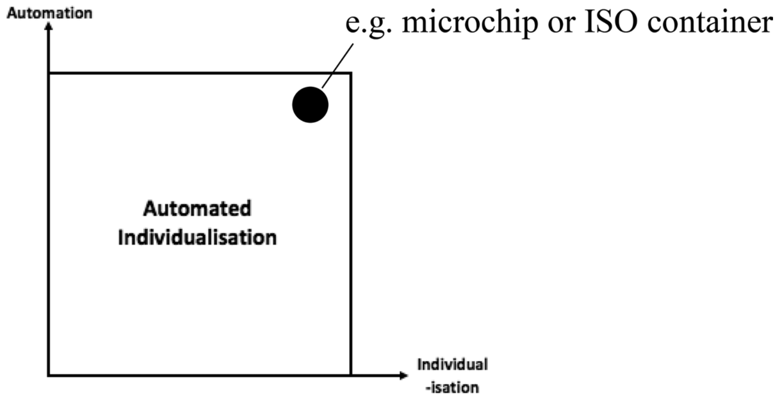

Figure 2. AM matrix from the manufacturing perspective.

Only occasionally can a technology combine automation and individualisation. That scenario is illustrated by the dot in the upper right corner of the matrix in figure 2. One rare example is the microchip that facilitated using computers for the automated processing of individual data. An example from beyond the digital arena is the ISO or intermodal freight container that facilitated the automated handling of goods that are transported on individual routes. Both examples led to a dramatic reduction in manual labour. An AM application combines high levels of automation and individualisation at the interface of the physical and digital arenas. AM allows the highly automated production of very individualised products like in-ear shells for hearing aids or the Invisalign® dental brace. Such disruptive applications cannot be realised with other production technologies and are based not only on sophisticated AM processes but also on the development of specialised biocompatible polymers.

Third dimension—industry perspective

By combining the two matrices we can identify the third dimension of our magic cube of AM. Following the example of the microprocessor, some technologies not only combine automation and individualisation but also have an impact on more than one industry, often leading to an inter-industrial revolution, as exemplified by the current emergence of the digital economy. We argue that AM is a comparable technology at the interface of the physical and digital worlds, in that it influences not only a single industry but many. This claim is underpinned by well-known examples from fields including nanoscience, prototyping, tooling, medicine, the aerospace and automotive industries (Truscott *et al* 2007, Gartner *et al* 2015, Maresch and Gartner 2017). We illustrate the industry dimension with the z axis that connects the first two matrices and results in the magic cube of AM depicted in figure 3.

Discussion

We use the results of our research, the ‘magic cube’ model, to highlight the multidisciplinary potential of AM to spur disruptive innovation across industries. The economic potential of AM, given its current state of technological development, is represented by the segments in the upper right-hand corner of the cube (figure 4).

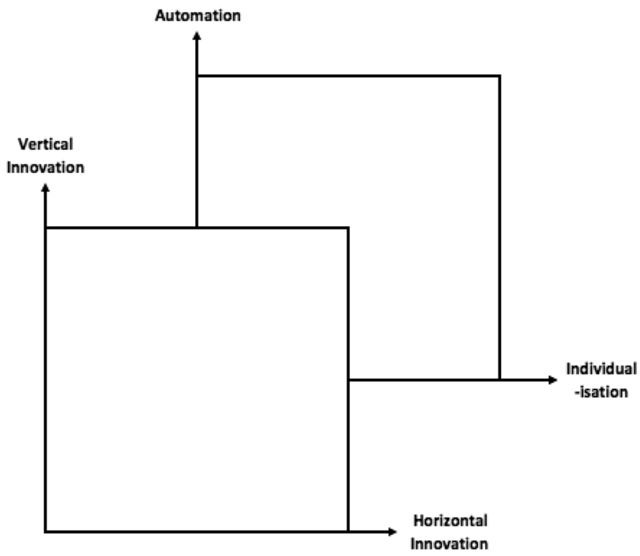

Figure 3. Missing link from the industry perspective.

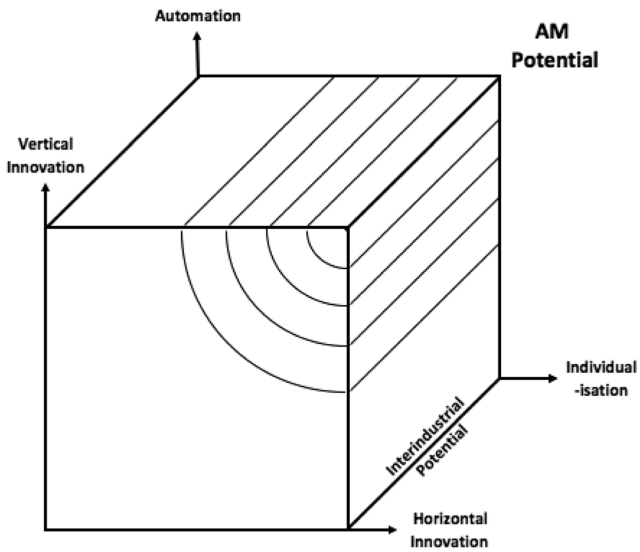

Figure 4. Magic cube of AM.

This area describes applications which not only need a high rate of automated individualisation but also call for a sophisticated interplay of more than one discipline, such as material science and machinery. In this area AM can outperform other manufacturing technologies, while traditional technologies reside along the lower left-hand side edge of the cube (Achillas *et al* 2017).

Future technology developments and economies of scale could enhance the potential of AM (Maresch and Gartner 2017, Gartner *et al* 2015), which would extend the circles towards the lower left-hand side of the cube. The dynamic perspective also means the cube could improve the understanding of developments in AM. While this paper seeks to extend understanding by focusing on the multidisciplinary interplay of AM processes and the materials they employ, other research might examine other aspects like creativity, the mastery of construction and (3D) designing, software and algorithm development, robotics and mechatronics, business models and management, or indeed any industry where AM is applied (e.g. medicine, aerospace, tooling, or the automotive sector) (Cautela *et al* 2014, Jing *et al* 2014, Gatto *et al* 2015, Tang *et al* 2016).

The practical value of the cube is its use to select application in a systematic way where most companies use AM without reflection as followers of the technological trend. Firms can identify those applications for AM that offer them the most attractive potential. It is important to note that for the assessment of a possible integration of AM in the value chain, firms have to think beyond the mere replacement of traditional production techniques, but have to consider the possibilities AM offers for a radical redesign of the entire value chain. The assessment also has to include the new features of products and services that the application of AM makes possible and the corresponding advantages for the competitiveness of the firms' market offer. Such additional features might more than offset higher costs of AM-based production (Maresch *et al* 2016).

In addition, the framework presented here could have applications beyond AM, such as in assessing other automated manufacturing techniques like computerised CNC-moulding, and other technologies often referred to as digital-manufacturing, albeit with some limitations. Readers should be aware that manufacturing industries are home to a wide range of substitution technologies that are beyond the scope of this paper, and that even the best technological solution is not necessarily the best solution in economic terms.

Conclusion

This paper presents an innovation research model that explains the specific potential of AM to spur disruptive innovation across a wide range of industries through multidisciplinary expertise and the realisation of automated individualisation. The framework sheds light on AM from three different perspectives. (1) The innovation perspective focuses on the tension between the vertical and horizontal innovation of research and development; (2) the manufacturing perspective focuses on the tension between the automation and individualisation manufacturing strategies; (3) the industry perspective combines the other two perspectives by establishing the arena for applications of AM across diverse industries. The resulting magic cube of AM not only helps to clarify frequent misunderstandings over the nature of AM, but also highlights the often-underestimated complexity of the application of AM. It becomes apparent that AM is an especially powerful production paradigm where other technologies suffer from the trade-off between horizontal/vertical innovation and/or specialisation/ individualisation. The framework can guide both researchers and practitioners seeking to identify the economic potential of AM. In addition, the model can be used in a non-static way to depict the development of the application of AM.

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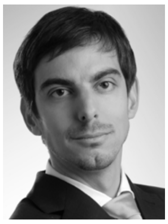

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