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Publication date:
2019

Document version:
Accepted manuscript

Citation for polished version (APA):
Blichfeldt, H., Knudsen, M. P., & Hannibal, M. (2019). *Development and Test of an Additive Manufacturing Maturity Model*. Paper presented at R&D Management Conference, Paris, France.

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Development and Test of an Additive Manufacturing Maturity Model

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Paper prepared for the R&D Management Conference 2019

Paris, France. June 17th–21st 2019

The innovation challenge: Bridging research, industry & society

Track: R&D Management

Abstract

Firms are confronted with rising competitive pressure on both the manufacturing and innovation processes to meet the ever-increasing demand for customization and individualization. Despite this, only sparse research has combined literature from operations management and innovation management literature to investigate the interaction between them. This paper develops an Additive Manufacturing Maturity Model to investigate the diffusion of AM technology and the possible positive impact of adopting AM technology on the innovative capabilities of the firm. Based on a survey in Danish manufacturing firms, this paper presents a novel perspective on the role of additive manufacturing (AM) technologies in facilitating the integration of production, innovation, and market perspectives in the business processes of firms. The results demonstrate that around 25% of the firms use AM technology. Furthermore, the results demonstrate a positive impact of the level of maturity on AM use and innovation. The paper shows that the used potential of AM technology is an indicator of potential competitive advantage for a firm. Derived from the findings, the paper proposes a theoretical model that integrates the scope of AM applications with the business processes of the firm. In this way, the paper contributes to the literature in technology management and to the relationship between the AM technologies and their associated competitive potentials. Furthermore, this paper specifically contributes to the much needed, but still scarce and fragmented literature, on decision models of AM, through an integrative perspective from innovation and operation management literature.

Keywords: Additive Manufacturing, 3D print, technology management, innovation, maturity model, manufacturing.

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1. Introduction

Globalization is pushing the boundaries of firms and force them to focus on finding ways to address the growing competitive pressure arising from increased demand for customization and individualization (Hu, 2013; Tseng & Piller, 2003). Firms and policy makers in developed countries are concerned with maintaining manufacturing in the home country, while focusing on increasing the innovative capabilities to push new solutions to the market (Gunday, Ulusoy, Kilic, & Alpkhan, 2011). The companies experience a pressure to reduce cost and increase productivity while meeting an increased demand for improved quality and product innovation. These pressures puts the manufacturing flexibility and speed at the front of the strategic agenda together with the demand for innovative competencies (Brettel, Klein, & Friederichsen, 2016; Colotla et al., 2016).

While research has already focused on these potential solutions – flexibility, speed, and innovative competencies – these have largely been addressed within their respective domains, manufacturing and innovation management (Chatha & Butt, 2015). This article argues that a yet unexplored potential can be found in the intersection between manufacturing studies and innovation management. Hence, this article connects the prevailing models of the two fields to investigate the linkages and potential synergies between innovation and manufacturing. Specifically, we do this by investigating the utilization of innovative technologies that are relevant for promoting competitiveness in both domains (Figure 1).

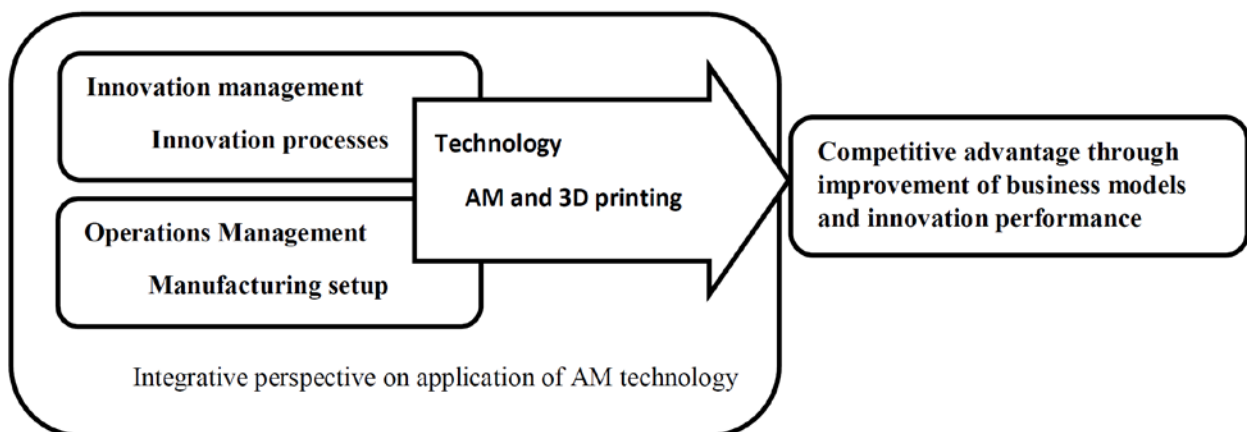


Figure 1: Research focus

3D printing technology is one such technology. Since the introduction in the 1980s, 3D printing technologies have mainly been used for rapid prototyping (RPT) as part of the innovation process

(Oettmeier & Hofmann, 2016). The technology is well-known and mature, nevertheless, additive manufacturing technology is fast developing to become a key enabling technology of this century (Lipson & Kurman, 2013). Although often used interchangeably, additive manufacturing (AM) utilize 3D printing technology. It is broadly accepted that AM has the potential to support the companies' need for building capabilities for innovation, manufacturing, and business activities to improve their competitiveness (Baumers, Dickens, Tuck, & Hague, 2016; Berger, 2017; D'Aveni, 2013; Gambell et al., 2017; Küpper et al., 2017; Wohlers, 2015).

With the positive prospects on the utilization of 3D print for the company needs, it would be obvious to assume that wide-spread adoption of the technology in industry can be observed. Some observe a significant increase in interest in industrial printers and related print services (Wohlers, 2019). CECIMO, a European AM association, state in their 2018 report that they see a development from the earlier focus on rapid prototyping towards more industrial purposes (CECIMO, 2018). There are however no studies, neither on European nor at national level (in Denmark) that document the rate of adoption of the technology in industry. Several causes to a relatively low utilization of the technology may be considered; lack of knowledge about the potential of the technology (what it can do for the company?), lack of competence in using the technology across domains (how may it be used by the company?), lack of managerial attention and willingness to invest in a technology that may be considered merely a technology-substitution (how is this bringing something new to the company?). In any case, we need to understand whether companies are in fact using these to their full potential – and what the possible benefits can be – seen in an integrative perspective.

Following these introductory remarks, the research aim of this article unfolds in two:

First, we aim to develop a theoretical model for AM maturity, which integrates innovation and operations management.

Second, we aim to investigate the maturity of Danish manufacturing firms and the effect of AM use on their competitiveness factors.

This article contributes to both the literature on strategic innovation management and manufacturing systems by developing an AM-maturity model for assessing a firm's maturity in use of AM technologies across multiple domains (innovation, tooling, and production). The model is based on theoretical arguments drawing from the competence-based literature and integrates the perspectives

to assess the effect of AM-maturity on innovation and manufacturing performance. The results demonstrate the expected positive effects of higher maturity on these performance measures.

2. From 3D printing to Additive Manufacturing – A Theoretical Underpinning

The three-dimensional print technology (3D print) has been under development for more than two decades (Kruth, Leu, & Nakagawa, 1998; Levy, Schindel, & Kruth, 2003) and has previously been used primarily for rapid prototyping and hence as support in the innovation process. Recently, however, this perspective on 3D print has been considered too narrow as reflected in the possible scope of applications of the underlying technology. The proposed terminology is now to talk of Additive Manufacturing, which also emphasizes that products are built on a layer-by-layer basis, through a series of cross-sectional slices (Berman, 2012; Gibson, Rosen, & Stucker, 2015: 1). Both Additive Manufacturing (AM) and 3D printing adhere to the definition by ASTM as: *a process of joining materials to make objects from 3D model data usually layer upon layer, as opposed to subtractive manufacturing methodologies* (ASTM International, 2012; Mellor, Hao, & Zhang, 2014).

Rapid prototyping (RPT) utilize the 3D print technology to speed up and value-add the design and development phase (Niaki & Nonino, 2017b), whereas additive manufacturing has its focus on the manufacturing of parts or products (Gibson et al., 2015). Different technologies and materials are advantageous depending on how it is utilized. In addition, the use and implementation of various AM technologies (FDM, SLA, SLS or Metal Binder Jetting) or choice of materials (plastics, composites, metal) have significantly different demand for knowledge- and technology capabilities as well as financing.

Based on this conception, it can be argued that 3D print is a technology, which can be characterized as a capital good (e.g., machines, tools, structures, etc.) serving a particular purpose – in this case, the printing of goods based on a digital drawing and using a layer-by-layer principle. The underlying understanding of the technology follows Bekar et al. (2018: 1007), who formulates that a technology refers to (i) *the process of applying knowledge to practical uses*; (ii) *specific machines or processes themselves*; and, (iii) *the knowledge of how to make things of economic value*. The main point of importance is that the technical knowledge is embodied in the capital good, which serves a specific use case. The above widening of the scope from using 3D printing for rapid prototyping to additive manufacturing reflects the potential and emerging multi-purpose use of the technology. 3D print may

accordingly not only be used for prototyping, but potentially also for other applications like production or production support purposes (Berman, 2012).

The widening of the use of the technology across a company can more precisely be pointed at three different domains. First, 3D printers have been used in Rapid Prototyping (RPT) to support the R&D and innovative processes. Second, printing technologies can be applied to print tools for manufacturing to support a more customized and flexible operations setup (Conner et al., 2014), and third, additive manufacturing can be used to manufacture components or products as finished items (Niaki & Nonino, 2017b). However, our understanding of the potential synergetic effects of multi-purpose use in companies are yet to be explored and understood.

3. Literature Review

Through an extended literature review of more than 1.100 articles, we identified 170 relevant articles from Web of Science, Scopus and other sources, which deal with aspects of additive manufacturing beyond the actual development of the print technology. That is, we focus entirely on the adoption of the technology within an industrial context. Much literature has focused on the potential of using 3D print for prototyping and hence innovation purposes (Candi & Beltagui, in press; Rayna & Striukova, 2016). The dominating research areas as inspired by Niaki and Nonino (2017a) within the field of Additive Manufacturing are; AM technology selection (Kengpol & O'Brien, 2001; Lan, Ding, & Hong, 2005), supply chain management (Durach, Kurpjuweit, & Wagner, 2017; Oettmeier & Hofmann, 2016), product design and production cost models (Mellor et al., 2014), manufacturing system frameworks (Achillas, Aidonis, Iakovou, Thymianidis, & Tzetzis, 2015), environmental aspects assessment (Ullah, Hashimoto, Kubo, & Tamaki., 2013), strategic challenges (Kruth et al., 1998), open-source innovation and business and social impacts (Sanchez, Boudaoud, Muller, & Camargo, 2014), and economics of AM (Weller, Kleer, Piller, & Hinke, 2014).

The application domains (innovation, tooling manufacturing and product/component manufacturing) of Additive Manufacturing are most often analyzed independently of each other, although a few examples of contributions that integrate across the different domains can be found. The term “bridge manufacturing” has been introduced where AM is seen as a bridging technology between prototype field test and small versus medium volume production (Berman, 2012). Companies will furthermore have a potential for building competitiveness through integration between design and manufacturing, requiring vertical integration in the values chain (Petrick & Simpson, 2015). Parts and product

manufacturing and manufacturing support (moulds for low volume) has been compared in the context of the production portfolio (Achillas et al., 2015). Finally, the adoption of Additive Manufacturing in both manufacturing and supply chain contexts based on the adoption terminology by Rogers (2003) has been proposed (Schniederjans, 2017).

The literature review has shown a lack of an integrative perspective, where the relationships between the application domains (innovation, manufacturing of tools and parts/products) and the adoption of the technology can be investigated. A few contributions on adoption of AM and the bridge between application domains are found, but the connection between technology maturity and the application domains is still not researched. This gap will be investigated by development and test of the Additive Manufacturing Maturity Model.

4. An Additive Manufacturing Maturity Model (AM-MM)

As has been made clear from the review of the literature, additive manufacturing is a multi-purpose technology, but the potential from integrating uses across different domains has yet to be identified and analyzed (Bellgran & Säfsten, 2012; Pour, Zanardini, Bacchetti, & Zanoni, 2015). An integrated perspective would allow us to better understand the relationships between different applications of AM technologies, and the AM maturity of the manufacturing companies. In reviewing the AM literature, only a few theoretical frameworks emerge (Achillas et al., 2015; Conner et al., 2014; Pour et al., 2015), and each of these deal with different elements and perspectives on AM.

The aim of a maturity model is to show the differences between immature and mature companies with respect to e.g. the adoption of a certain technology – here AM technology. In an immature company, the AM technology has not yet been adopted, and the company may in general also have a very low knowledge about the technology including how it may be used in the processes of the company. A characteristic of a maturity model is that it should distinguish between those companies that have no knowledge and no use of the technology and those companies that have a mature or advanced use and high technical capability in understanding the technology, its potential for application across domains, and for being integrated fully into the processes of the firm.

In this article, we argue that an AM maturity model (AM-MM) should include the application domains (innovation/prototyping; production support; production) and the knowledge and competence of a firm of the technology. The least mature companies have no current use of the

technology and no real knowledge of the technology, whereas the most mature companies will have applied the technology in all 3 domains and have rather advanced knowledge of the technology.

Application Domains

Innovation has been both argued and demonstrated to be a key competitive priority of firms. A body of literature has demonstrated positive effects of innovation on economic performance (Camisón & Villar-López, 2014; Junge, Severgnini, & Sørensen, 2016) despite many firms struggling to successfully commercialize their technology (Simula, Valiauga, & Lehtimäki, 2014) and fail in innovation (Panne, Beers, & Kleinknecht, 2003; Tranekjer, 2017).

To develop better products that better suit customer needs, rapid prototyping can deliver a fast representation of different product forms and functions, which clients can test and provide feedback to during the development process (Gibson et al., 2015: 1). In the innovation process, which may be represented as unfolding in several stages from the early idea to concept development and on to prototyping and validation (Frederiksen & Knudsen, 2017: figure 1), 3D printers as well as other technologies like simulation tools may be utilized for testing and validating the innovative concept.

An additional benefit from adopting e.g. 3D print for innovation purposes was forcefully put forward by Damanpour and Gopalakrishnan (2001), who argued that a firm's competitiveness over time depends on its ability to adopt new technologies i.e. a firm's ability for process innovation, and to develop product innovation. The adoption of 3D print (or other technologies) for the purpose of supporting the business processes of the firm follow the definition of a process innovation as; *new elements introduced into an organization's production or service operations (e.g., input materials, task specifications, work and information flow mechanisms, and equipment) to produce a product or render a service* (Damanpour & Gopalakrishnan, 2001: 48), which follow from the original work of Utterback and Abernathy (1975). Hence, besides the direct benefits of employing the 3D print technology for testing and validating the innovative solution, the literature also argues synergies between process and product innovation (see e.g. Gunday et al., 2011).

A *manufacturing system* is a sequence of operations, equipment, machines, people and procedures, that can carry out operations (Groover, 2016). The manufacturing system aim to fulfill the customer demand, based on input from market (customization), product innovations (R&D) and process

innovations (technology adoption) (Rothwell, 1994). A manufacturing system can be conceptualized as a system in which the product is transformed from design to a market ready product through a value creating process. The manufacturing system (MS) can deliver several competitive priorities, often described as quality, delivery, cost (Ward, McCreery, Ritzman, & Sharma, 1998), flexibility, performance, and innovativeness (Miltenburg, 2008). To deliver on these customer specified priorities, the manufacturing system can be further divided into production systems (PS), parts production systems (PPS), and assembly systems (AS) (Bellgran & Säfsten, 2012). There are multiple ways of combining the production system components into a flexible setup resulting in new product introduction, re-design and re-engineering of products. The most common manufacturing paradigm builds on Design for Manufacturing (DFx) that focus on the design process to complete products ready for manufacturing (Chu et al., 2016). The DFx approach is challenged by the increased demand for adoption and adaptation to innovation. By introducing Manufacturing for Design (MFD), the manufacturing paradigm becomes more agile towards design and complexity and can be realized through hybrid manufacturing utilizing flexible production systems including additive manufacturing (Chu et al., 2016).

The capabilities of both manufacturing and production systems are directly linked to innovation through the manufacturing levers as human resources, process technologies and organizational structures (Miltenburg, 2008).

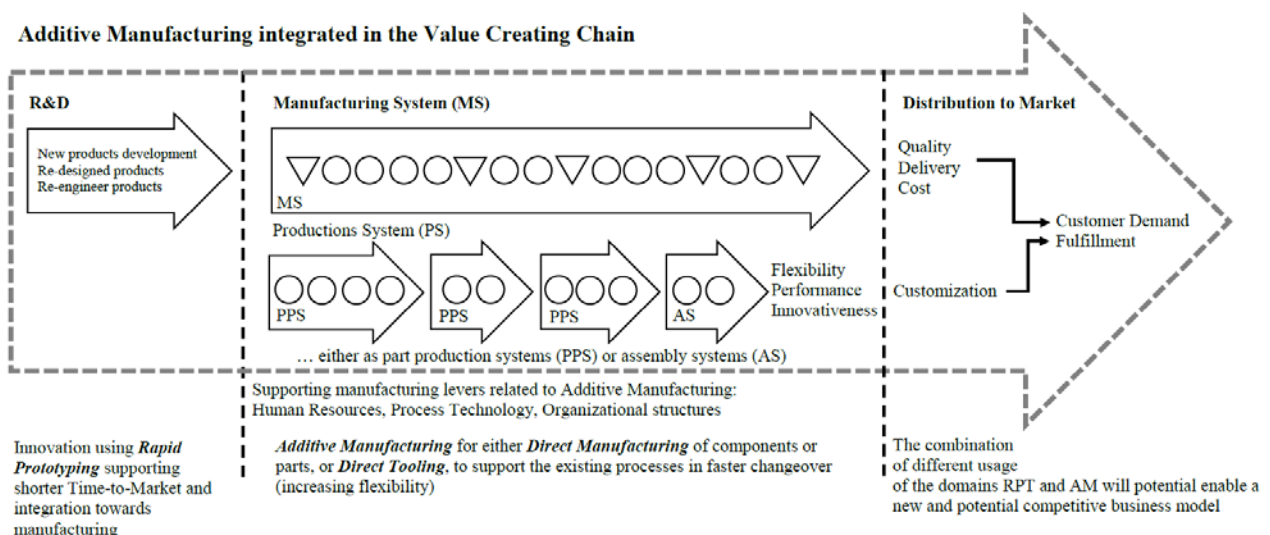


Figure 2: The manufacturing system

Figure 2 illustrates the integration between R&D, the manufacturing system and market access (Distribution to market). The underlying production systems enable flexibility, product performance, and innovativeness (ability to introduce innovation to the system). The level of customization capability depends on the level of human resources, process technologies and organizational structures. It is our view that additive manufacturing technology has the potential impact to fulfill MFD as it operates in different domains.

AM maturity level

A literature review specifically oriented towards maturity and readiness level for Additive Manufacturing did not result in any contributions. A few maturity or readiness models were identified but these relate either to product technology or manufacturing technology (Peters, 2015). These models measure readiness on a scale, which is based on the fundamental technology readiness scale^{iv}. Although, these models provide a framework for assessing the current maturity of either a single product technology or manufacturing technology, they fail to include the maturity or the technology capability of e.g. the manufacturing setup or other technology-based systems.

As there are no established maturity or readiness indexes available, inspiration has been found in Moore's "Chasm model" from 1991 (Moore, 1991), which provides a company categorization in relation to adoption of new technology. Others have also applied the model to technology studies (see e.g. Schniederjans, 2017; Sroufe, Curkovic, Montabon, & Melnyk, 2000).

The model

This article proposes that AM maturity is an important factor for understanding how well the firm is equipped to strategically unleash the potential for competitive strength. We argue that maturity can be seen as a combination of basic knowledge about the technology – *getting to know about the technology* – and competence in using the technology – *being competent in using the technology*.

As a new technology is introduced on the market, the first information provides a basis for the company to consider whether the technology is relevant for the firm or not. At the second level of maturity, the firm has obtained some knowledge about the technology, but at this stage, the firm has

^{iv} https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html

yet to put the technology into use, i.e. no investments have been made. The firm first engages into trial and error to learn about the specific opportunities offered by the technology – a process of *getting acquainted with the technology*. At the third level, the firm makes its first initial exploration and trials with the technology. Over time, as a consequence of using and learning about the technology, the firm’s maturity level increases. We therefore argue that maturity is related to the single technology, here AM technology.

The theoretical model (Figure 3) integrates AM maturity in terms of knowledge about the technology and the application or use domains (innovation (rapid prototyping), production support (direct tooling) and part production (direct manufacturing)). By adoption of the *Chasm model* (Moore, 1991), we argue that the higher maturity level a company achieves combined with its activities in use domains have a positive effect on the company competitiveness derived from AM technology. A further insight from the Chasm model, is the expected distribution of firms across the different knowledge and use levels.

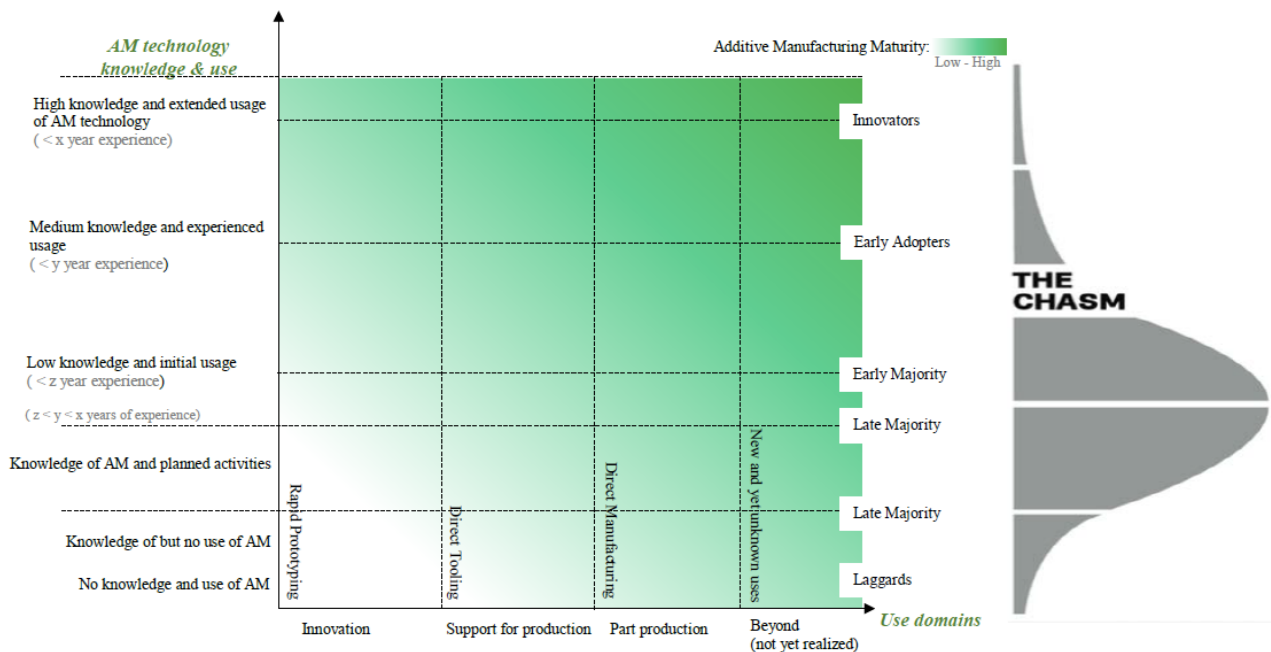


Figure 3: The AM Maturity Model

The figure illustrates the adopters on the right-hand side, and the maturity model as the combination of knowledge and domain use on the left-hand side. The lowest maturity level is seen in the lower left-hand corner (the *laggards*; c.f. Moore), where the firms have no knowledge and no use. In the

upper right-hand corner, we see the most advanced users that have high knowledge and extended use, which covers several use domains (the *innovators*).

5. Research Design

The data used to analyze the maturity model was collected as part of a national screening of manufacturing companies in relation to their AM readiness^v. The screening was carried out as a combination of a survey and follow-up case studies. 2 pilot studies (one expert and a representative company) were carried out prior to administering the survey to the survey population. The survey was subsequently sent to the population of Danish manufacturing firms (NACE code 10-33) with more than 20 employees. The population was further enlarged by adding 20 firms with a particular association to 3D print and additive manufacturing that were not part of the original population.

Data was drawn (18-04-18) from the databases Orbis and Bisnode. Bisnode produced 2.503 Danish manufacturing firms (NACE 10-33) with 20+ employees registered at a Danish address. Orbis returned 2.017 firm meeting the same criteria. The two lists were merged to a gross list consisting of 2.957 firms. This list was subsequently cleaned for firms without a valid email and firms located in Greenland or the Faroe Islands. This resulted in a total population for the survey of 2.334 Danish manufacturing firms.

An invitation to participate was forwarded to the firms in the population in May 2018. In Mid-May non-responding firms were called. We assumed that firms with no knowledge and no use of AM technology would have a lower propensity to respond as a result of lower or no interest. For the screening and the assessment of maturity it is however important that we try to ensure a fair and representative representation in the final data set. We therefore sampled firms and contacted them by phone. Two email reminders were sent to all firms; the last of these reminders was sent out in Mid-June. The data collection ended June 22, 2018.

Representativeness of the data sample

The survey resulted in 314 responses equaling a response rate of 13.5%. The dataset was subsequently cleaned for entries with missing data resulting in a final dataset for analysis of 286 firms (response

^v This article acknowledges the funding obtained for the national screening by the Danish AM Hub (<https://am-hub.dk/en/>).

rate 12,4%). The data set was tested for and confirmed to be representative of the Danish population of firms with 20+ employees on size and geography. The sample indicate a dominance of small to small-medium sized firms, which is also the case for the entire population.

Size	No. of employees	Total population	Distribution	Total responses	Share of sample
Small	20-49	1.265	54,2	140	48,9
Small-medium	50-99	543	23,3	71	24,8
Medium	100-199	286	12,2	47	16,4
Large	200+	240	10,3	28	9,8
Total		2.334	100	286	100

Table 1: Comparison of firm distribution – population and sample

The distribution of firms on geography is also representative of the general population of manufacturing firms with 20+ employees, with 15% of the respondents located in the larger Copenhagen area, 11% in the remaining parts of the Zealand region, and 33%, 18% and 23% in the Mid-, North- and South-Jutland regions. In addition to these factors, the data set was also screened for representativeness on industry. The data cover 23 NACE codes in all. The largest group of respondents belongs to *Manufacture of fabricated metal products, except machinery and equipment* (NACE-group 25). These represent 20% of the sample, and the second largest group of firms represent 18% of the firms and belongs to *Manufacture of machinery and equipment n.e.c.* Both groups match the distribution observed in the total population of Danish manufacturing firms.

Finally, we checked the level of technology intensiveness (EUROSTATs standard) of the firms as it can be expected that the firm's association with e.g. technology intensive industries have a higher propensity to adopt new technology. 63% of the firms are within low to medium-low technology intensiveness, which again corresponds well to the population of Danish manufacturing firms.

Variables and analytical approach

The model was tested with simple distributions and frequencies. To further understand the importance of AM maturity for the firms, we further tested the relationship between AM maturity and the firm's ability to benefit from the technology in terms of innovation performance. Innovation performance is measured using the variable *Product Innovation*, which was measured as a simple yes/no question:

Has your firm introduced products that were new to the firm (not updates or simple upgrades to existing product program) in 2015, 2016 or 2017? The share of firms that are innovative is 71.3%.

We further distinguished between firms with product innovation and those where the products were new to the market (i.e. radical innovation). The share of firms with radical innovation is 38.8% and of the innovative firms 49.7% have performed radical innovation.

Similarly, for *Process Innovation*, we asked if the firm has introduced new technologies (besides AM print technology) in 2015, 2016 or 2017. The share of firms with process innovation is 33.5%.

25% of the manufacturing companies in the data sample use AM technologies, either as an external service (8%), has purchased own printer (6%) or as a combination (11%). This compounds to AM ownership in 17% of the firms. Further, there is a clear relationship between the level of technology intensity and the use of print technologies as high technology firms are also more prone to use AM technology.

The preferred print technologies are dominated by the relatively simple FDM (Fused deposition) technology, which is the technology also used by hobbyists. There is also some use of SLA (light exposure of resin fluid) and SLS (laser sintering in powder) technologies, which are still fairly easy to use technologies.

The main external motives for adopting the AM technology is the *new potential market opportunities*, whereas *pressure from customers and competitors* is less significant. The internal motives for adopting AM technology is significant for *fast prototyping*, *quick validation of prototypes* and *development purposes*. Factors like *time to market* and *fast part production* are less important. This observed R&D driven motivation and the predominant use of relatively simple AM technologies focused on prototyping are in line with the trends described by Oettmeier and Hofmann (2016).

6. The AM Maturity Model - Findings

The manufacturing companies are organized into four main categories based on the AM maturity model. The categories are:

1. Non-users with no AM awareness, neither competencies or knowledge.

2. Outsourcing the AM competencies to a services or technology provider, possessing application knowledge.
3. In-house ownership or leasing of the technology, building both knowledge and competencies.
4. Combining AM technology ownership and outsourcing of specific tasks or services.

This categorization indicates a gradually increasing maturity level for the companies (the y-axis in Figure 3). The second category illustrates the actual usage of AM technology in the three domains (x-axis in Figure 3):

1. Product development (rapid prototyping).
2. Production support (direct tooling of molds, fixtures, supporting tools for production).
3. Parts production (direct manufacturing).

All cases using AM (either owning, leasing, or purchasing the service) have also assessed the *used potential of the technology* on a scale from low-> medium-> high for each usage domain. We argue that the *used potential of the technology* is an indicator of extensiveness of use and therefore of AM competence.

It is our expectation that more extensive knowledge, more diverse use across domains and more varied competence as developed through own use and through interaction with suppliers of prints result in higher AM maturity. The higher competence and use variety translate into improved competitiveness factors as seen in innovation performance and business performance.

Of the 286 cases, 214 (74.8%) did not use AM print technology and are accordingly placed in the lower left-hand side of the corner. 24 firms (8.4%) purchase services from technology or service providers, but do not own any printers. 48 firms (16.8%) owned their own technology (including a sub-group, which also purchased services from technology providers) – see also the y-axis in Figure 4.

27 companies are active in only one usage domain (colored black in Figure 4), 25 companies are active in two domains (colored red), and 20 companies are active in all three domains (colored green). Figure 4 is therefore showing the firms (excluding the non-users) as a combination of AM technology knowledge and use and the number of domains they are active in. The score next to the bubbles illustrate the extent of use on average for the firms with that specific maturity level.

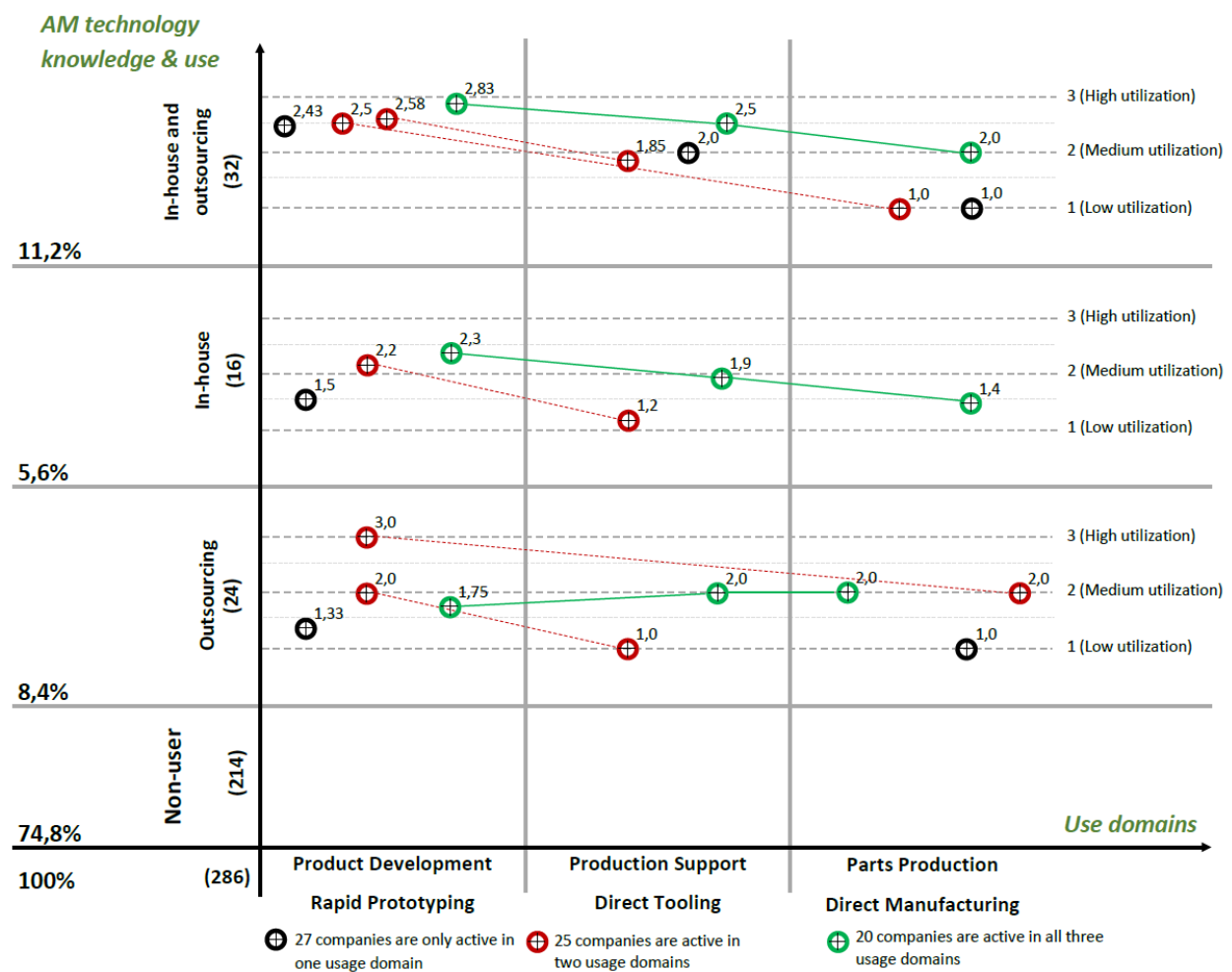


Figure 4: AM Maturity Model – Findings

As an example, in the box with *Outsourcing* and *Product Development* shows one black bubble represented by 15 firms (20,8% of the firms; excluding the non-users. See also Table 2). These have on average a relatively low utilization of the potential of the technology (1.33 on average). On the other hand, 14 companies (19,4%) have the combination of *Inhouse* and *Outsourcing* combined with *Product Development* & *Production Support* (two domains; marked with red color). These have a much higher utilization of the technology with an average of 2,58.

The group of firms active in the *product development* and *production support* domains, who have the AM technology in-house has been marked with a red color. The group of companies has been plotted in the section between the *In-house* and the two relevant domains. In the *Product development* domain, the companies on average score used potential of the technology to 2.2 (maximum score 3). In the *Production support* domain, the average score is 1.2. It can therefore be seen that the companies

possessing their own AM printer and that are active in the two domains (Product development and Production support) have a higher used potential of their technology within Product development than in Production support.

Figure 4 shows that the highest level of used potential of the technology is found in the product development domain. The parts production domain has in general a lower *used potential of the technology* than the tooling domain.

Second, the more domains a firm is active in, the higher their level of used potential of the technology. Companies active in all the domains have a significant higher level of used potential of the technology, than those active in only two domains.

Third, the higher the maturity level of the company, the higher the level of used potential of the technology. In other words, companies that both own and source AM technology competencies, has an overall higher level of used potential of the technology compared to companies sourcing the AM services or only printing on in-house AM printers. This indicates that companies seem to be able to maximize the benefits through engaging in a mixed approach involving both own AM activities and collaboration with external partners. The complexity in different AM technologies could explain that the mixed approach has the highest potential.

Table 2 now illustrates the frequency of each combination of AM technology maturity. The table shows that the most frequent patterns are:

Product development: 24 companies (33,3% of the categorized firms; excluding non-users). This corresponds to the expected highest penetration of the technology as the technology was first and foremost used for innovation purposes.

Product Development & Production Support: 21 companies (29,2% of the categorized firms; excluding non-users). Based on the high use in product development and the expected evolutionary path moving into tooling, it is also following our expectation about the increase in maturity.

Product development, Production Support & Parts Production: 20 companies (Represented by the green lines; 27,8% of the categorized firms; excluding non-users). Perhaps most surprising that almost 30% of the firms combine the use of AM technology for product development and tooling with parts production. These firms will according to our model be the most mature firms; the

innovators. Especially, the 6 companies that both have own technology and outsourcing have a very high utilization of the technology (average of 2,83).

	In-house & out-sourcing	In-house	Outsourcing	Total	Non-user	
Product development	7	2	15	24 (33,3%)	214 (74.8%)	
Production support	1	0	0	1 (1,4%)		
Parts Production	1	0	1	2 (2,8%)		
Product Development & Production Support	14	5	2	21 (29,2%)		
Product development & Parts Production	3	0	1	4 (5,6%)		
Production Support & Parts Production	0	0	0	0 (0,0%)		
Product Development, Production Support & Parts Production	6	9	5	20 (27,8%)		
Total	32 (44,4%)	16 (22,2%)	24 (33,3%)			
				72	214	286







Table 2: Distribution of firms on different maturity levels (following Figure 4)

AM Maturity and Effect on Business Model

In addition to tracking and classifying the sample firms in relation to AM maturity and domain use, the data sample also us to analyze how AM technology has impacted the firm's business model and innovation performance. The responding manufacturing companies has been asked if their interaction with AM technology have had influence on their business, e.g. change in business model or development of such. The analysis points to a higher impact on the business model, the higher level of AM maturity the companies hold. In the group with companies only sourcing AM technology, 29% have experienced a positive impact on their business model. In the group of companies that own their own AM technology, 56% of the companies experience a positive impact on their business. At the highest level of AM maturity (companies that both insource and outsource the AM technology), 63% of the companies experience a positive effect.

AM Maturity and Effect on Innovation

Tables 3 and 4 present results on the relationship between company activity in the use domains and AM maturity level and respectively product innovation (incremental and radical) and process innovation.

Company AM activity within use domains; product development, production support and parts production	Product innovation		Process innovation
	Incremental	Radical	
Use AM in all three domains	85%	65%	60%
Use AM in two domains*	 88%	 72%	 52%
Use AM in one domain*	 66%	 30%	 26%
No use of AM technology	52%	24%	22%

* Use domain is unspecified

Table 3 Company AM activity in domains compared with product and process innovation

Table 3 shows that AM technology activities are significantly related to the innovative capabilities, both with respect to product and process innovation. Hence, only 24% of the companies with no use of AM technology have introduced a radical new product innovation (from 2015-2017). It is however more significant that moving from activities in one domain into two or three will influence the innovative output even more. Especially, the share of firms introducing a radical innovation increases from 30% to 72%, which indicate that bridging between domains based on AM technology increases the innovative capabilities, particular resulting in radical innovation.





Company AM maturity level	Product innovation		Process innovation
	Incremental	Radical	
Level 4: Inhouse + outsourcing	81%	56%	47%
Level 3: Inhouse	 81%	50% 	 63%
Level 2: Outsourcing	75%	54% 	29%
Level 1: Non-user	52%	24%	22%

Table 4 Company AM maturity level compared with product and process innovation

Table 4 shows the relationship between company AM maturity level and product- and process innovation. For firms introducing new products, the most significant difference is in the transition from being non-user to user, either through service/technology provider, or technology owner. The

process innovative firms show a different pattern, and the change in process innovation is primarily relevant when changing from outsourcing of the AM technology to investing in own technology. 29% of the companies not owning AM technologies are also process innovative, whereas 63% of the companies, who own their own AM technology also are process innovative. This indicates the importance of building knowledge and competencies through ownership.

Therefore, we see that technology ownership supports (based on maturity level) the development of incremental innovation, whereas integration across application domains using the technology supports the highest level of radical innovation.

7. Discussion and Contribution

In contrast to additive manufacturing, subtractive manufacturing (Gibson et al., 2015) consists of more traditional manufacturing process as drilling, grinding, milling, turning and cutting. Both additive and subtractive processes are part of a manufacturing system (process level) that transforms and adds value to products (Slack, Chambers, & Johnson, 2010). This paper has explored the role of AM and 3D printing technology in bridging the different potential use domains – from product development to parts production (and maybe later new uses – yet to be identified). Our findings showed that AM is indeed a multi-purpose technology and the better utilization of the potential also impacts the innovative capabilities and the business model. We therefore, find that the integrative perspective holds great potential for further theorizing.

We propose an integrative conceptual framework (Figure 5), which draws on the distinct innovation process model (Frederiksen & Knudsen, 2017) and manufacturing system (Bellgran & Säfsten, 2012) to provide a multi-domain perspective on Additive Manufacturing. Based on the foundational innovation model (on the top), we identify the use of additive manufacturing for rapid prototyping (marked with (1)). The second and third domains for the use of AM is the support to the production through tooling (marked with (3)) and the parts production (marked with (2)). We further anticipate that the AM technology will allow the firm to capture input from the market – either from the prototype tests and validation – or from user experience with the final parts. In both ways, the input will serve as market feedback to the innovation process (marked with (4)). Finally, the impact of using AM technology results on the business model was briefly analyzed – and was positive. This impact may be further understood as effects in terms of business and service development by providing customer solutions (marked with (5)).

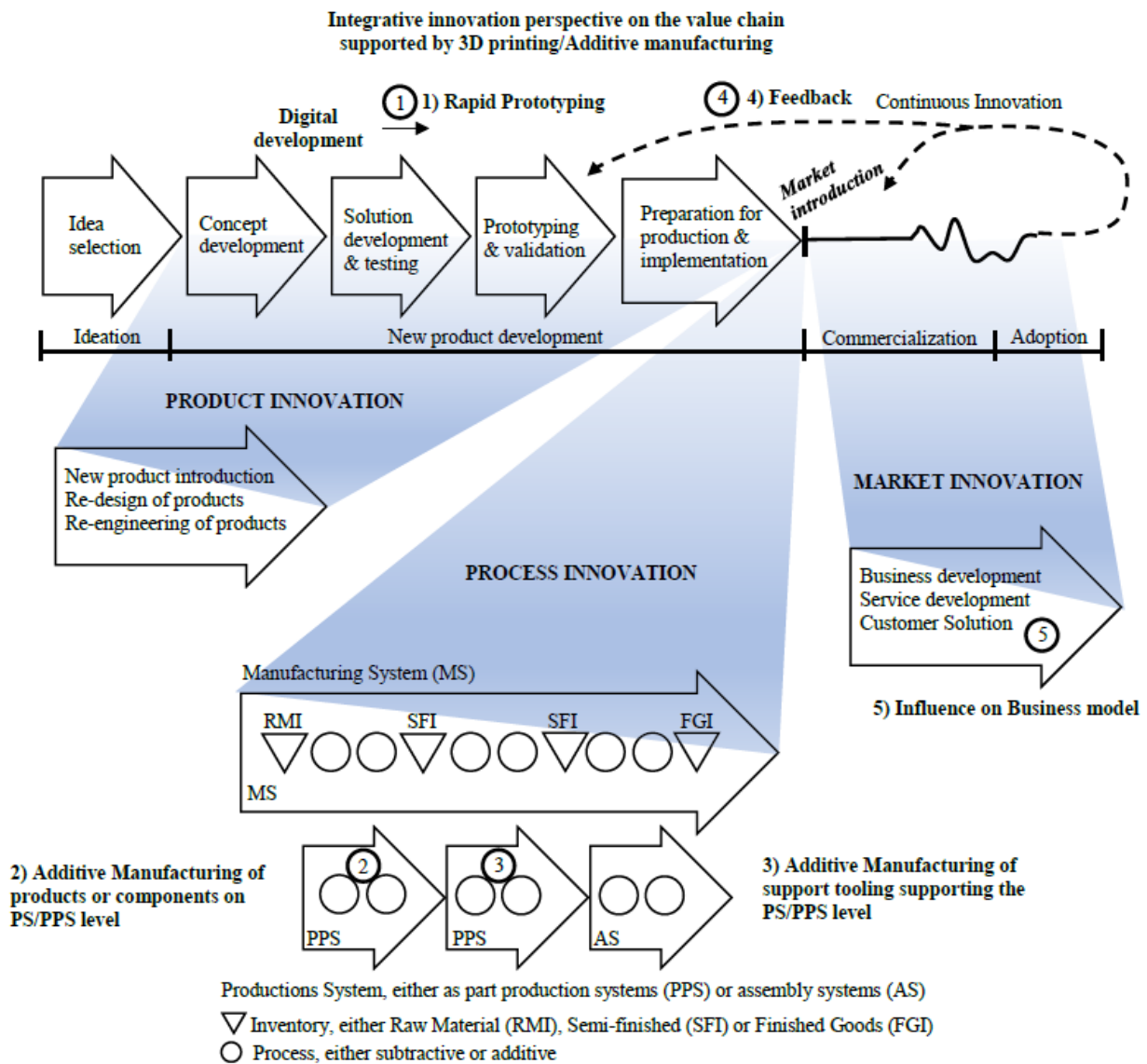


Figure 5: Integrated Innovation and Manufacturing Perspective utilizing Additive Manufacturing as driver.

In more details, this model illustrates some interesting features. We expect that Rapid Prototyping (1) in the innovation chain will combined with digital development provide shorter time-to-market, higher potential for customization, customer integration in the development (concept and solution phase. Specifically, digital testing (FMEA/FEA) and simulation tools will have cost reducing potential. Additive manufacturing (2) of products and components will support product complexity, use of advanced materials, less material waste, and flexibility in terms of customization. Additive manufacturing of support tooling (3) such as grippers, molds and fixtures increase the manufacturing flexibility and enable faster changeovers, small batch production and agility in the production setup. In this case, AM is not the direct manufacturing process, but provides shorter lead-time on tooling

components. As additive manufacturing becomes an integrated manufacturing technology, a feedback loop (4) to the design and development chain appears, as new opportunities within design, materials and changeability becomes available (maybe a change from design for manufacturing to manufacturing for design). For the competitive priorities (see figure 1), we expect that there will be a potential for higher level of customization, customer integration in the development process, and shorter lead-times in both development and manufacturing (5).

Contribution

This paper contributes to the literature on technology management in the analysis of the relationship between AM technologies and their associated competitive potentials as moderated by increased integration across the core processes of industrial firms. This article therefore identified the need for a cross disciplinary and integrative approach by developing a maturity model of AM technology. The findings on AM maturity and innovative capabilities provided the basis for a new model of an integrative innovation and manufacturing perspective. We propose that the core mechanisms – labelled 1 through 5 – are further conceptualized and tested empirically.

In a broader perspective, emerging technologies can potentially impact various level and functions in the industrial value system, as conceptualized in “the coupling model of innovation” (Rothwell, 1994; figure 3, p. 10). Particularly, we notice other emerging technologies with similar properties like sensors, robotics, drones and Internet of Things, which may both contribute to and benefit from the insights on industrial dynamics obtained in this study. This paper therefore contributes to the much needed, but still scarce and fragmented literature, on decision models of AM (Oettmeier & Hofmann, 2016; Pour et al., 2015). We stress that this is only the first small step in assessing the potential of AM in specific manufacturing contexts.

References

- Achillas, C., Aidonis, D., Iakovou, E., Thymianidis, M., & Tzetzis, D. 2015. A methodological framework for the inclusion of modern additive manufacturing into the production portfolio of a focused factory. *Journal of Manufacturing Systems*, 37: 328-339.
- ASTM International. 2012. Standard Terminology for Additive Manufacturing Technologies, Vol. F2792-12a. West Conshohocken, PA: ASTM International.
- Baumers, M., Dickens, P., Tuck, C., & Hague, R. 2016. The cost of additive manufacturing: machine productivity, economies of scale and technology-push. *Technological Forecasting and Social Change*, 102: 193-201.

- Bekar, C., Carlaw, K., & Lipsey, R. 2018. General purpose technologies in theory, application and controversy: A review. *Journal of Evolutionary Economics*, 28: 1005–1033.
- Bellgran, M., & Säfssten, K. 2012. *Production Development: Design and Operation of Production Systems* London: Springer-Verlag London.
- Berger, R. 2017. Additive Manufacturing – next generation AM: Roland Berger GmbH.
- Berman, B. 2012. 3-D printing: The new industrial revolution. *Business Horizons*, 55(2): 155-162.
- Brettel, M., Klein, M., & Friederichsen, N. 2016. The Relevance of Manufacturing Flexibility in the Context of Industrie 4.0. *Procedia CIRP*, 41: 105-110.
- Camisón, C., & Villar-López, A. 2014. Organizational innovation as an enabler of technological innovation capabilities and firm performance. *Journal of Business Research*, 67(1): 2891-2902.
- Candi, M., & Beltagui, A. in press. Effective use of 3D printing in the innovation process. *Technovation*, 80-81: 63-73.
- CECIMO. 2018. Voice of the European Additive Manufacturing Industry. Brussels: European Association of the Machine Tool Industry and Related Manufacturing Technologies.
- Chatha, K. A., & Butt, I. 2015. Themes of study in manufacturing strategy literature. *International Journal of Operations & Production Management*, 35(4): 604-698.
- Chu, W.-S., Kim, M. S., Jang, K. H., Song, J. H., Rodrigue, H., Chun, D. M., Cho, Y. T., Kol, S. H., Cho, K. J., Cha, S. W., Min, S., Jeong, S. H., Jeong, H., Lee, C. M., Chu, C. N., & Ahn, S. H. 2016. From Design for Manufacturing (DFM) to Manufacturing for Design (MFD) via Hybrid Manufacturing and Smart Factory: A Review and Perspective of Paradigm Shift. *International Journal of Precision Engineering and Manufacturing-Green Technology*, 3(2): 209-222.
- Colotla, I., Fæste, A., Heidemann, A., Winther, A., Høngaard Andersen, P., Duvold, T., & Hansen, M. 2016. Winning the industry 4.0 race; How ready are Danish manufacturers?
- Conner, B. P., Manogharan, G. P., Martof, A. N., Rodomsky, L. M., Rodomsky, C. M., Jordan, D. C., & Limperos, J. W. 2014. Making sense of 3-D printing: Creating a map of additive manufacturing products and services. *Additive Manufacturing*, 1-4: 64-76.
- D'Aveni, R. A. 2013. 3D printing will change the world *Harvard Business Review*, 91(3): 22-22.
- Damanpour, F., & Gopalakrishnan, S. 2001. The Dynamics of the Adoption of Product and Process Innovations in Organizations. *Journal of Management Studies*, 38(1): 45-65.
- Durach, C. F., Kurpjuweit, S., & Wagner, S. M. 2017. The impact of additive manufacturing on supply chains. *International Journal of Physical Distribution & Logistics Management*, 47(10): 954-971.
- Frederiksen, M. H., & Knudsen, M. P. 2017. From Creative Ideas to Innovation Performance: The Role of Assessment Criteria. *Creativity and Innovation Management*, 26(1): 60-74.
- Gambell, T., Blackwell, E., Dhawan, R., George, K., Marya, V., Singh, K., & Schmitz, C. 2017. The great re-make: Manufacturing for modern times.
- Gibson, I., Rosen, D., & Stucker, B. 2015. *Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing*. New York: Springer New York.
- Groover, M. P. 2016. *Automation, Production Systems, and Computer-Integrated Manufacturing* (4th edition, global edition ed.): Pearson.
- Gunday, G., Ulusoy, G., Kilic, K., & Alpkan, L. 2011. Effects of innovation types on firm performance. *International Journal of Production Economics*, 133(2): 662-676.
- Hu, S. J. 2013. *Evolving Paradigms of Manufacturing: From Mass Production to Mass Customization and Personalization*. Paper presented at the Forty Sixth CIRP Conference on Manufacturing Systems 2013, Setubal, Portugal.
- Junge, M., Severgnini, B., & Sørensen, A. 2016. Product-Marketing Innovation, Skills, and Firm Productivity Growth. *Review of Income and Wealth*, 62(4): 724-757.
- Kengpol, A., & O'Brien, C. 2001. The Development of a Decision Support Tool for the Selection of Advanced Technology to Achieve Rapid Product Development. *International Journal of Production Economics*, 69(2): 177–191.
- Kruth, J. P., Leu, M. C., & Nakagawa, T. 1998. Progress in Additive Manufacturing and Rapid Prototyping. *CIRP Annals*, 47(2): 525-540.
- Küpper, D., Heising, W., Corman, G., Wolfgang, M., Knizek, C., & Lukic, V. 2017. Get Ready for Industrialized Additive Manufacturing: The Boston Consulting Group.

- Lan, H., Ding, Y., & Hong, J. 2005. Decision Support System for Rapid Prototyping Process Selection through Integration of Fuzzy Synthetic Evaluation and an Expert System. *International Journal of Production Research* 43(1): 169–194.
- Levy, G. N., Schindel, R., & Kruth, J. P. 2003. Rapid Manufacturing and Rapid Tooling with Layer Manufacturing (Lm) Technologies, State of the Art and Future Perspectives. *CIRP Annals*, 52(2): 589-609.
- Lipson, H., & Kurman, M. 2013. *Fabricated: The new world of 3D printing*: John Wiley & Sons.
- Mellor, S., Hao, L., & Zhang, D. 2014. Additive manufacturing: A framework for implementation. *International Journal of Production Economics*, 149: 194-201.
- Miltenburg, J. 2008. Setting manufacturing strategy for a factory-within-a-factory. *International Journal of Production Economics*, 113(1): 307-323.
- Moore, G. A. 1991. *Crossing the Chasm. Marketing and Selling Technology Projects to Mainstream Customers*. New York, NY. : Harper Business.
- Niaki, M. K., & Nonino, F. 2017a. Additive manufacturing management: A review and future research agenda. *International Journal of Production Research*, 55(5): 1419-1439.
- Niaki, M. K., & Nonino, F. 2017b. Impact of additive manufacturing on business competitiveness: A multiple case study. *Journal of Manufacturing Technology Management*, 28(1): 56-74.
- Oettmeier, K., & Hofmann, E. 2016. Impact of additive manufacturing technology adoption on supply chain management processes and components. *Journal of Manufacturing Technology Management*, 27(7): 944-968.
- Panne, G. v. d., Beers, C. v., & Kleinknecht, A. 2003. Success and Failure of Innovation: A Literature Review. *International Journal of Innovation Management*, 07(03): 309-338.
- Peters, S. 2015. A readiness level model for new manufacturing technologies. *Production Engineering*, 9(5-6): 647-654.
- Petrick, I. J., & Simpson, T. W. 2015. 3D Printing Disrupts Manufacturing: How Economies of One Create New Rules of Competition. *Research-Technology Management*, 56(6): 12-16.
- Pour, M. A., Zanardini, M., Bacchetti, A., & Zaroni, S. 2015. *An Economic Insight into Additive Manufacturing System Implementation*. Paper presented at the IFIP International Conference on Advances in Production Management Systems, Tokyo, Japan.
- Rayna, T., & Striukova, L. 2016. From rapid prototyping to home fabrication: How 3D printing is changing business model innovation. *Technological Forecasting & Social Change*, 102: 214–224.
- Rogers, E. M. 2003. *Diffusion of Innovations* (5th ed. ed.). New York, NY.: Free Press.
- Rothwell, R. 1994. Towards the Fifth-generation Innovation Process. *International Marketing Review*, 11(1): 7 -31.
- Sanchez, F. A. C., Boudaoud, H., Muller, L., & Camargo, M. 2014. Towards a Standard Experimental Protocol for Open Source Additive Manufacturing. *Virtual and Physical Prototyping* 9(3): 151–167.
- Schniederjans, D. G. 2017. Adoption of 3D-printing technologies in manufacturing: A survey analysis. *International Journal of Production Economics* 183: 287–298.
- Simula, H., Valiauga, P., & Lehtimäki, T. 2014. Technology versus product innovations - are they like apples and oranges? A comparative study on commercialisation. *International Journal of Technology Marketing*, 10(1): 25-46.
- Slack, N., Chambers, S., & Johnson, R. 2010. *Operations Management* Harlow: Financial Times Prentice Hall.
- Sroufe, R., Curkovic, S., Montabon, F., & Melnyk, S. A. 2000. The new product design process and design for environment, "Crossing the chasm". *International Journal of Operations & Production Management* 20(2): 267-291.
- Tranekjer, T. L. 2017. Open innovation: Effects from external knowledge sources on abandoned innovation projects. *Business Process Management Journal*, 23(5): 918-935.
- Tseng, M. M., & Piller, F. T. 2003. *The Customer Centric Enterprise: Advances in Mass Customization and Personalization* (1st edition ed.): Springer
- Ullah, A. M. M. S., Hashimoto, H., Kubo, A., & Tamaki, J. I. 2013. Sustainability Analysis of Rapid Prototyping: Material/ Resource and Process Perspectives. *International Journal of Sustainable Manufacturing* 3(1): 20–36.

- Utterback, J. M., & Abernathy, W. J. 1975. A dynamic model of process and product innovation. *Omega*, 3(6): 639-656.
- Ward, P. T., McCreery, J. K., Ritzman, L. P., & Sharma, D. 1998. Competitive Priorities in Operations Management. *Decision Sciences*, 29(4): 1035-1046.
- Weller, C., Kleer, R., Piller, F. T., & Hinke, C. 2014. *Economic Implications of 3D Printing: Market Structure Models Revisited*. Paper presented at the Academy of Management, Philadelphia, Pennsylvania.
- Wohlers, T. T. 2015. Wohlers report 2015: 3D Printing and Additive manufacturing State of the Industry Annual Worldwide Progress Report. Fort Collins, Colorado: Wohlers Associates.
- Wohlers, T. T. 2019. Wohlers report 2019: 3D Printing and Additive Manufacturing - State of the Industry. Annual Worldwide Progress Report. Fort Collins, Colorado: Wohlers Associates.