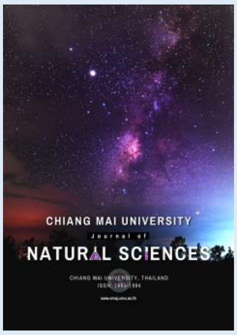

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Research article

Additive Manufacturing: Application Perspectives in Small and Medium Enterprises

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Abstract Changes in customer expectations, markets and organisations are creating an increasing need for customised products and calling for reactive supply chains. New technologies might help organisations to deal with these challenges in a flexible and cost-effective way. One of these technologies is Additive Manufacturing (AM). The object of this paper is to outline the potential of AM in production, to identify possible supply chain developments and to determine the role that SMEs might play in this scenario. In detail, we pose the question whether AM might lead to geographically dispersed manufacturing plants and might replace physical material flow with information flow and how SMEs can act in this development process. Based on an exploratory literature review, we highlight the market requirements addressed by AM, the supply chain characteristics for AM and the role of SMEs. Implementing AM can cause shifts in the decoupling point as well as changes in the global supply chain configuration (relocation of production closer to the final customer). We then conduct some expert interviews, which confirm some of the results of the literature review, but emphasise that AM will not replace conventional manufacturing processes on a large scale, at least in the medium term.

Keywords: Additive manufacturing, 3D printing, Industry 4.0, Manufacturing systems, Supply chain design

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INTRODUCTION

Additive Manufacturing (AM) first emerged in the 1980s, but it has only recently achieved a technological breakthrough (Sasson and Johnson, 2016). AM has the potential to revolutionise the way of producing and delivering products. It bears, in fact, significant technological advantages for some industries: it allows to produce lightweight structures (aerospace), to reproduce parts (automotive) and to realise precision models (medicine) (Wong and Hernandez, 2012). The literature points out that specific characteristics of AM support its successful application (Hagl, 2015). The main advantages and potentials of AM are that complex geometries can be produced economically, functionalities can be integrated into geometry design and product-related tools and final assembly are not needed. Further, products can be manufactured at any location, generated directly from suitable 3D data and several products can be manufactured simultaneously in one process. Finally, a continuous change of the materials during the production process has been increasingly implemented, thus enabling other component characteristics (Gebhardt, 2014; Khoo et al., 2015). Besides these advantages, unit costs and batch sizes determine the successful implementation of AM (Lachmayer et al. 2016). Therefore, it is becoming a key enabler for manufacturing (Kumar, 2018) and is applicable in niche segments (Rylands et al., 2016). AM offers new development possibilities for SMEs, to produce more cost-effectively, specialise in certain production areas or offer custom-made products (BMWI, 2019). There is a lack of SME-based studies on the adoption of Industry 4.0 technologies within the current scientific literature (Mittal et al., 2018). AM challenges and solutions in SMEs are not discussed in the literature except for one paper (i.e., Martinsuo and Luomaranta, 2018). However, this paper is focused more on challenges in AM adoption and how to overcome them than on SMEs application perspectives. Among advanced production technologies, AM could favour differentiation strategies in niche markets and might support SMEs to position themselves in the international competition. However, the advantages of AM and the market requirements that might arise through AM need to be examined in detail. In addition, there is a further need to understand the supply chain settings imposed by AM (Martinsuo and Luomaranta, 2018).

The goal of this paper is, therefore, to shed light on possible application perspectives of AM in small and medium-sized enterprises (SMEs). In more detail, we seek to answer to the following research questions: (1) whether AM might lead to geographically dispersed manufacturing plants and might replace physical material flow with information flow and (2) how SMEs can act in this development process. We first conducted a literature review to highlight the market requirements addressed by AM, the supply chain characteristics for AM and SME specific characteristics that open new application perspectives. We then carried out five expert interviews. These interviews showed that, in the future, SMEs may play a bigger role in the application of AM than large-sized firms (Rogers et al., 2016) and substantially impact global supply chain configurations (Sasson and Johnson, 2016).

MATERIALS AND METHODS

To answer the research questions, we conducted a literature review focused on the following three main topics: (1) the market requirements (customer needs) that might be addressed through AM; (2) the characteristics of supply chains for AM and (3) the role of SMEs in this changing environment.

To gain a deeper insight into the potential applications of AM in production, we then conducted some expert interviews. Our research design is based on exploratory interviews, i.e., a qualitative research methodology that comprises unstructured, personal and oral questioning to gain in-depth information. Following Fischer-Rosenthal and Rosenthal (1997) we formulated semi-structured questions allowing the interviewee to talk freely on the following topics: areas of AM application, potential in production, challenges related to production, future developments and possible changes in the value chain. We used a maximum variation sampling strategy and selected five experts in five different areas of knowledge to maximise the input diversity (Patton, 2002). We selected the experts based on their knowledge in the research field. They had to be responsible for research and/or development of projects or at least be familiar with the AM technology and its technical or economic aspects. Based on the abovementioned requirements, the following five experts have been interviewed: two experts involved in AM research and development projects; two experts active in AM projects in industry (dental and automotive industry); and one expert who did significant research on AM for his dissertation in material science and technology (Table 1).

Table 1. Interviewed experts.

No.	Position	Institution
I1	Team Leader AM / Engineering Technologies	Research Institute
I2	Project assistant & PhD candidate	University (Material Science and Technology)
I3	General Manager R&D	Company - Dental industry (SME)
I4	Researcher	Research Institute
I5	Team Leader Technology Application	Company – Automotive industry (large company)

RESULTS

Literature review

To shed light on application perspectives of AM in SMEs, we conducted a literature review focusing on three topics: (1) the market requirements (customer needs) that might be addressed through AM; (2) the supply chain characteristics for AM; and (3) the role of SMEs in AM application.

Market requirements for AM. The European technology platform ManuFacture has analysed visions and plans for the development of manufacturing in Europe and identified the following eight megatrends: Ageing, Individualism, *Knowledge in the global ICT, Globalisation, Urbanisation, Sustainability, Finance, Public debt* (Westkämper, 2014). These megatrends might act as drivers for change. As an example, ICT reduces transaction costs, thus increasing the benefits of spreading (R&D, manufacturing and marketing) activities across a broad geographic area. This substantially changes the relationships between players in the global supply chains and increases the competitive pressure. Similarly, global competition is forcing companies with high customer individuality and product complexity to adopt shorter lead times.

To satisfy the diverse needs of customers, companies should offer a broader range of services and product variants. The trend towards mass customisation has been intensified in the last few years. While differentiation generally increases complexity and costs along the entire supply chain, mass customisation seeks to combine differentiation and cost leadership. Within the company, individualisation and shrinking batch sizes require well-synchronised production processes as well as an efficient linking of business areas (product development, production, logistics, IT and sales). However, this is not enough; close inter-company collaborations (with suppliers and other partners) are also fundamental. Supply chains need, in fact, to be flexible and, at the same time, efficient (BMWi, 2015).

In sum, the increasing demand for individual products, shorter product life cycles, shorter product development and delivery times, and the request for higher product quality and additional services pose new challenges for the manufacturing industry (Bullinger and Warnecke, 2003). In the future, business processes and supply chains will be more complex, and complexity will increase further if no suitable control-approaches are found for production and logistics (Rodenhäuser and Rauch, 2015).

Industry 4.0 technologies might represent a control-approach that supports flexible and efficient production while connecting the entire supply chain to a digital network (BMWi, 2015). It allows, in fact, to create networks that organise and optimise themselves across organisations in real time. These networks can be designed according to different criteria, such as costs, availability or resource consumption (VDI, 2014). Industry 4.0 concepts are therefore, expected to play a central role in the competition of countries, industries and companies and AM may act as an enabling technology for the changes of Industry 4.0 (Fratocchi, 2018). AM could favour differentiation strategies and the production of individualised products at lower costs, enabling mass production and shorter lead times (Lindemann et al., 2006).

Supply Chain characteristics for AM. The supply chains characteristics for AM encompass the following aspects: (1) supply chain goals; (2) decoupling point; (3) supply chain structure; and (4) location choices.

'Supply Chain goals' depend primarily on the industry and the product (Melzer-Riedinger, 2007). Fisher et al. (1997) identify two main product categories: *functional products* and *innovative products*. Due to their different characteristics, these two types of products require totally different supply chains.

Functional products satisfy the basic needs of customers (these are standardised goods). The demand is stable or predictable and the variety is low. The supply chains of these products need, therefore, to be physically efficient (i.e., to reduce production costs and to keep a high production capacity utilisation). In this case, the supply chain pursues the goal of maximising product performance while keeping production capacity utilisation constant and lead times and costs low. Processes in the steel, chemical and paper industries pursue these goals and follow a push production system. In push production, products are manufactured to stock and provided centrally for the customer (Melzer-Ridinger, 2003, 2007).

The demand for innovative products is not predictable. For innovative products, it is important to gain early sales with high profit margins, because of their short product life cycles (<1 year). Flexible and market-responsive supply chains are also needed to reduce lead times and to postpone the decoupling point (Fisher et al., 1997).

The '*decoupling point*' is the point in which an order passes from an anonymous make-to-stock production to a (customer-specific) make-to-order production (see Figure 1). A decoupling point at a later stage (postponement) can help to reduce inventory levels and to meet the goal of market-responsive supply chains (which better meet the customer requirements) but it leads to higher production costs (Arndt, 2008).

'Push production' encompasses continuous manufacturing to stock whereas *pull production* is market-oriented and requires a customer order to start the production process (Melzer-Ridinger, 2003; 2007). *Push production* puts economic efforts in the foreground and pursues the goals of high capacity utilisation and low inventories; delivery and lead times are of secondary importance. The stock in the warehouse needs to be at least high enough to maintain a predefined service level. In *pull-production*, it is, instead, important to guarantee a high level of delivery reliability and to adhere to the delivery times required by the customers. This approach automatically leads to a lower utilisation of the production machines. If production capacity is expanded, additional costs will negatively impact unit costs. In this case, customers could decide whether and to what extent they want to accept shorter delivery times for higher prices (Nyhuis and Wiendahl, 2012).

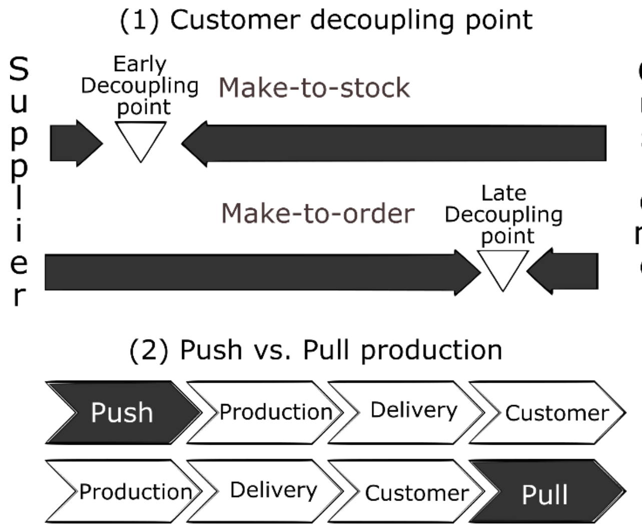

Figure 1. **Manufacturing planning control strategies.**

AM offers the possibility to print products directly from suitable 3D data and it can satisfy unpredictable demand, thus, enabling suppliers to act quickly and flexibly, building up capacity, keeping lead times short and eliminating processes that are superfluous. The product is tailored to the customers' requirements in the early stage of product development. This enables an early decoupling point and, at the same time, an individualised product that is tailored to the customer order (Figure 2).

Figure 2. **Shifting the decoupling point to an early stage through AM.**

The '*supply chain structure*' (or supply chain design) encompasses a set of decisions related to the actors that perform the different stages of the production and logistics processes and the relationships among them. These decisions should be aligned with the supply chain goals. Companies need to decide the governance mode to adopt for each activity ("Make or Buy" decisions). Three main configurations can be identified (see, among others, Kummer et al., 2013):

- Pure external procurement: Products are only purchased from suppliers.
- Pure in-house production: Products are only produced in-house.
- Mixed forms: A combination of external procurement and in-house production.

AM technologies increase the collaboration between suppliers and customers, i.e., some machine suppliers have become material suppliers in the AM industry. This change can be attributed to the immaturity of the technology (lack of material suppliers) and is probably a strategy of the machine suppliers to protect their businesses (Mellor et al., 2013).

Figure 3 displays four possible scenarios for supply chain configurations with the implementation of AM.

(1) *In-house production:* The production takes place within the company. For this purpose, the know-how and CAD-data need to be available. In-house production offers some main advantages: (a) parts are available immediately, (b) good profits are possible at high capacity utilisation (c) know-how can generate competitive advantages (Gebhardt, 2013).

(2) *External manufacturing – service provider:* Products are produced by an external service provider, who is specialised in AM. The company itself only delivers the CAD-data and still holds the production know-how. The company benefits from a lower investment needed in AM machines and prices do not depend on production capacity (Gebhardt, 2013).

(3) *External manufacturing – customer:* The customer "prints" the parts himself. The CAD-data are delivered; however, the customer has the possibility to influence the product development process. Hence, the company's relationship with its customers changes.

(4) *New value adding business models.* Service providers focusing on product development offer platforms where the customer can download the desired CAD-file and "print" it at home (Fastermann, 2014).

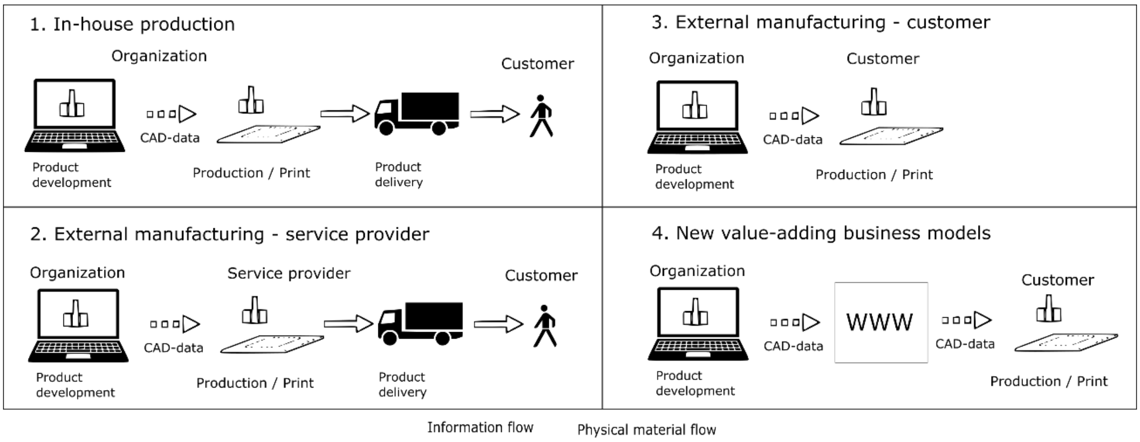

Figure 3. Supply chain structures for AM (adapted from August-Wilhelm Scheer Institut, 2016).

Bergmann (2004) describes the development of future production concepts and highlights that production will move from industrial mass production to small and flexible production facilities. Within this context, companies will create mobile factories, connected to each other like modular systems of individual elements, that can be quickly built and dismantled (Bergmann, 2004). While the geographical distance to the customer has so far limited the organisational flexibility (Picot et al., 2001), these mobile factories will enable companies to adapt quickly to local needs and changes in the market, and to deliver cost-effectively.

Finally, the implementation of AM technologies influences the '*location decisions*' of manufacturing plants. Since no tooling is required, the implementation of the technology may result in a redistribution of manufacturing sites closer to the demand. In theory, the AM only requires CAD-data and the raw material for production (Mellor et al., 2013; Mishra, 2016). In addition, AM processes have the potential to replace physical material flows in the value chain with information flows (3D data). The physical transport of components may be substituted by decentralised production close to the customers. This assumption is also based on the premise of a single-stage production: the component is manufactured in a single process, directly from the digital data and assembly steps are omitted. Therefore, AM processes can potentially lead to decentralised production. The implementation of AM in SMEs may enable flexible adaptation to local demand (on-site production) and shorter delivery times and turn to a success factor. However, in most cases, the consideration of an "on-site production" might be limited by the technical fact that the AM products still need to be (re)finished with traditional processes (Fastermann, 2014; Lachmayer et al., 2016).

The role of SMEs. Smart manufacturing poses greater challenges to SMEs than to large companies. SMEs are, indeed, generally not well-involved into external knowledge networks (e.g., with universities), are financially constrained, and lack technical resources (Mittal et al., 2018). The current literature discusses various challenges in adopting AM in different supply chain positions and how SMEs can overcome these challenges. Martinsuo and Luomaranta (2018) and Rauch et al. (2017) find that AM needs to be adopted along the whole supply chain. They argue that manufacturing SMEs and SMEs in an AM supply chain need to overcome: (1) technological challenges, such as long production time, size constraints and price constraints; and (2) organisational challenges, such as missing knowledge and skills and the need to promote AM adoption (Martinsuo and Luomaranta, 2018). Given the changing market requirements, SMEs tend to highly customise their products and to shorten time to market (Kochan and Miksche, 2017). SMEs have experience in specific areas and knowledge for specialised products that can differentiate from their competitors, and strong customer/supplier relations. Hence, SMEs are more likely to produce specialised products in small batch-sizes (Mittal et al., 2018). Lachmayer et al. (2016) demonstrate that AM is adopted primarily in individually customised production (batch size 1) due to the high degree of design freedom. AM might, therefore, offer advantages for specialised SMEs in niche areas/industries, such as in the bio-medical or aerospace industry. These are industries in which SMEs smart manufacturing technologies are more likely to be adopted (Mittal et al., 2018; Lemu, 2019).

Empirical evidences (expert interviews)

The literature review carried out has shown that AM processes can offer advantages for customising products and producing complex parts. AM allows, in fact, to manufacture components or products in small batches, up to individual pieces, and produce geometries that could not be manufactured conventionally. Interviewee I1 describes custom-made products realised with AM: *'Parts of some very high-priced cars can be produced; i.e. individual wheel caps or purely steering wheel inserts, or other metal parts that are specifically designed for the customer.'*. This might represent a great opportunity for SMEs since they often highly customise their products (see the section "the role of SMEs").

Experts agree that AM will be increasingly adopted in fields where its advantages might be exploited. Interviewee I4 believes that AM might support production: *'in areas where these classical advantages of additive manufacturing are applied, such as function integration, lightweight construction, and assembly integration. i.e. the aerospace industry.'* Interviewee I2 is of the opinion that AM cannot compete with conventional manufacturing processes, such as milling or turning, for large production because of the higher costs: *'AM is simply too expensive for large scale production, the process is just too slow. Maybe on a small scale, AM might be cheaper.'* Hence, AM might be suitable for producing smaller lots. Interviewee I3 noticed in this regard that *'in the dental industry laser sintering [an AM technology] is suitable for producing prototypes, but also for producing small batches up to 200 pieces.* Interviewee I4 agrees that, *'in most cases AM is still too expensive. However, there are some exceptions where the advantages of AM and individualization increase the value of a product.'* Small lot production might help SMEs to integrate themselves in the competitive landscape.

The consensus is, therefore, that AM might be applicable in niche markets. Interviewee I2 explains this as follows: *'there will be niche markets where it makes sense to use AM. In these cases, AM can produce parts, that cannot be made conventionally. Further, it will be necessary to rethink the product design for AM, e.g., in lightweight construction. Products that used to be manufactured and assembled can now be produced in one piece.'*

AM can be successfully applied in processes where topologically optimised components or bionic structures are required. Compared to conventional processes, AM offers advantages in producing complex geometries. Smaller batch sizes (~10 pieces) produced with AM might also be cheaper than conventional manufacturing.

Interviewee I4 explains when using AM makes sense: *'It may be cheaper to produce some complex shape associated to special properties with AM than conventional. It is not effective to design a component in such a complex way that it must be produced with AM, because in this case there is no added value for the customer. There must be added value for the customer. i.e. the direct comparison of* *functional costs or production costs.'* In general, the interviewed experts do not consider AM to be applicable in areas that are characterised by extreme price pressure.

Experts also agree that AM certainly has potential in financially powerful sectors such as aerospace and medical technology. Interviewee I1: *'Financially powerful industries, such as aerospace and medical technology, are, in my opinion, certainly an application in the metal sector.'*

To sum up, according to most experts, AM is not a substitution technology. Interviewee I1 explained this as follows: *'AM does not simply replace another manufacturing technology, but a complete rethink will be necessary. On the one hand, this relates to the value chain itself, meaning its horizontal integration. On the other hand, AM affects entire value-creation networks and also, the vertical integration along the value chain. AM will have an impact on the product life cycle, the innovation processes; the business models, and the after-sales i.e. spare parts management.'*

Few studies have shed light on the characteristics of supply chains for AM. Their main finding is that AM is more suitable for innovative products and it might lead to decentralised production (closer to the customers). One of the experts involved in research and development emphasised the shifts in the supply chains characteristics required by AM. Interviewee I4 referred to a possible shift towards decentralisation in production (Production on Site) and the relocation of production closer to the customer, seeing some possible shifts in the value chain: *'It is quite possible that the production may be relocated to the vicinity of the customer. The development of new business models, especially in connection with spare parts management are imaginable. Companies sent the product file directly to the customer and he prints them in a copy shop nearby.'*. The proximity to the customer can offer business opportunities for SMEs who can take care of the design and/or printing of the products.

In conclusion, experts agree that AM might impact some industries, such as the aerospace and the biomedical engineering sector, economically. However, AM is only reasonably applicable if the specific advantages of the technology can be exploited. In other words, AM needs to add extra value to a product, that a conventional production process could not. This applies when products are tailored to the customer's order or when the customers design the products themselves. Interviewee I4 described such a customisation approach in the dental industry as follows: *'One AM potential is customer individualization, because on the one hand I can simply have the customer design the product individually via software, via parameterizations, via online applications and then manufacture this product very easily, without long setup times, without great effort, without great preparation. Invisalign is an American company that produces tooth rails for tooth correction and the company produces about 100,000 teeth per day with additive technology offering individualized mass production.* This shows that AM could not only be interesting for small series, but also for individualised large series. The interviewed experts believe that the focus on individualisation will increase and AM will find its major application in niche markets. Targeting a niche market might offer significant opportunities to SMEs, due to their specialised know-how and their flexibility (Akbar and Wadood, 2013).

DISCUSSION

The successful implementation of a new technology is influenced by external factors (such as market requirements and value-adding paradigms) and internal factors (supply chain goals and structure). Mellor et al. (2013) have considered both external drivers and the internal corporate strategy in their conceptual framework for determining whether AM should be implemented as production process or not (Mellor, Hao and Zhang, 2013).

This paper showed that the successful application of AM in SMEs will depend not only on the technical and economic aspects, but also on customer requirements and market expectations about the products and the supply chains. From a strategic point of view, the market requirements for AM have been analysed. The market requirements are an essential factor for the success of AM and, based on them, companies should define their supply chain goals, their supply chain structure and locations.

Since various goals might be set by SMEs, depending on the industry and the product, an overall solution on how to modify the supply chains to apply AM is not available. However, we can expect that AM and Industry 4.0 development will increase the demand for individual, constantly new and innovative products with shorter product life cycles. Therefore, in future, we expect supply chain goals focusing primarily on short product development times and on pull production. Table 1 gives an overview on possible application perspectives of AM and on the consequent required characteristics of supply chains.

Within this context, SMEs need to be aware of their strengths and recognise their essential success factors with AM at an early stage, to face competition and to take advantage of the market opportunities at the right time. AM production benefits from low economies of scale; this allows SMEs to obtain a cost-efficient production.

Table 2. Possible application perspectives of AM.

Characteristics of AM	***Possible development paths***
No additional individualisation costs	Shifting the customer decoupling point to the front of the value chain.
No additional costs due to complexity	Shifting the value creation to the product development / construction.
Shifting value creation to product development (a significant share of value-added lies in the design stage).	Option 1: In-house production - Know-how in design; Option 2: External production by external service provider - Know-how in design; Option 3: External production by the customer - Increased customer integration; Option 4: Completely new value-added opportunities and business models (e.g., platforms).
Manufacturing components in one step, directly from the digital data	Substitution of material flows with information flows, integration of customers into product development.
Production possible at any location	Mobile production, which enables shorter delivery times.
No final assembly necessary	Single-stage production: no value-added process of assembly. This enables shorter cycle times and delivery times.
Tool-free production	Smaller lot sizes
Production of several products in one step	Shorter lead times

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