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Research article

Potential of the Application of Additive Manufacturing Technology in European SMEs

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Abstract Production companies are forced to react quickly to increasing individualisation, a trend towards on-demand production and shorter delivery times. The key to deal with the new challenges is the ability to change to low volume production of customised artefacts. New manufacturing strategies and technologies are necessary to meet these specific requirements. The transition from traditional or centralised manufacturing systems to decentralised and distributed manufacturing systems shows a possible way to achieve local on-demand production and customisation of products. To enable economic low volume production, the implementation of additive manufacturing as manufacturing technology is becoming an interesting option for many manufacturing companies like small and medium-sized enterprises. In this work, the authors define key validation criteria for the assessment of the potential of additive manufacturing. Based on these criteria and the NACE classification of industrial sectors, the research team identifies potential industry sectors for additive manufacturing. Using statistical data from EUROSTAT database, the research team finally quantifies the potential of additive manufacturing in European SMEs.

Keywords: Additive Manufacturing, Advanced Manufacturing Technology, Distributed Manufacturing Systems, Industry 4.0, Smart Manufacturing

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INTRODUCTION

The United Nations Industrial Development Organization (UNIDO) highlights in their 2013 report, "Emerging trends in global manufacturing industries", the importance of non-sector-specific megatrends that affect global industrial economies (UNIDO, 2013). Besides globalisation, which leads the ranking, sustainability, accelerating product lifecycle and changing consumer habits also play a central role (Da Silva Andrade et al., 2015; Tao et al., 2017). Also the direction towards distributed manufacturing systems (DMS) is among the emerging trends expected to enable a more efficient use of resources and a production on-demand close to the customer (Matt and Rauch, 2013; Rauch et al., 2016). The classic structure in traditional manufacturing systems requires the shipment, manufacturing and assembly of the material in a centralised factory. The finished products are finally delivered to the customer leading to long supply chains and delivery times as well as difficulties in the consideration of individual customer wishes. The basis of distributed manufacturing strategies consists of the decentralisation concept, which implicates dislocated units of fabrication, where the manufacturing and assembly processes occur close to the customer (Almada-Lobo, 2016). DMS are very often more complex from an organisational point of view and less economic due to lacking economies of scale. Nonetheless, some of the key requirements, which are triggered by the specified megatrends, such as globalisation, sustainability and varying consumer preferences, can be satisfied (Mourtzis et al., 2015). DMS support the global market development through the geographical dispersion and simultaneously focus on the satisfaction of local consumer needs. The so-called "glocal" production has positive impacts on the sustainability, logistics cost, as well as delivery times. In addition DMS strategies can be easily applied in small and medium-sized enterprises (SME) as the concept foresees the production in small and highly flexible production units (Rauch et al., 2016).

The proximity to costumers allows capturing their requests and understanding their habits, but it is not a guarantor for a successful customisation. The process, which starts with the consumer-needs analysis, requires the development of basic conditions. Two of the fundamental factors that permit to implement successfully the individualisation of products are flexibility and adaptability of the fabrication systems in terms of product variety and volume. One of the emerging technologies that seems to ensure the fulfilment of these requirements is additive manufacturing (AM), also known as three-dimensional (3D) printing. It is defined by the American Society for Testing and Materials (ASTM) as 'the process of joining materials to make objects from 3D-model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining' (ASTM Standard, 2013). AM was developed in the mid-1980s with the aim to manufacture physical prototypes used as conceptual and functional elements in order to reduce the duration of the product development phase, as well as the time to market of new products (Kruth et al., 2007). Starting with rapid prototyping (RP) as one of the most appreciated technologies in product development, the technological diffusion led to the development of rapid manufacturing (RM), which is defined by Hague et al. (2003) as 'the production of end-use parts from additive manufacturing systems.'

Along with large share (consumer products, industrial machines, motor vehicles) interests and small and medium manufacturers, the medical and aerospace sectors can also be related to advanced niche SMEs, and not only to multinational companies and universities. In particular, metal AM systems are widely used in these markets (Shah and Mattiuzza, 2018). SMEs very often fail to recognise the full potential of modern technologies (Chiadamrong and O'Brien, 1999). According to Achillas et al. (2015), SMEs should evaluate the costs and benefits from the introduction of AM alternatives in their production based on their factory concept and strategy. SMEs' role in the future of AM may be even larger than that of bigger global players (Rogers et al., 2016) because SMEs adopting AM may be capable of transforming themselves into direct digital supercentres (Sasson and Johnson, 2016). However, the adoption of AM in SMEs is currently poorly understood, as the majority of the literature focuses on large firms, or a mix of firms of different sizes.

Thus, the purpose of this paper is to analyse the potential of AM technology in small and medium-sized enterprises in order to give SMEs a guideline if AM could be an interesting technology for increasing their business or not. The paper is structured as follows. After this introduction, follows a section giving an overview of the theoretical background and providing a description of distributed manufacturing systems, AM and their adoption in SMEs. Afterwards follows a brief overview of the research approach used in this research. The following section describes each single activity conducted by the research team to obtain the findings. In a first step, the authors define key validation criteria for the assessment of the potential of AM in different industrial sectors. In a second step, the research team identifies potential industrial sectors for the application of AM using the European NACE sector classification structure. For the most promising industrial sectors, the research team then quantifies the potential number of SMEs in Europe, where AM shows the highest potential of adoption. The findings of this study are critically discussed before ending with a brief conclusion and outlook for future research needs and activities.

MATERIALS AND METHODS

Theoretical Background

UNIDO (2013) examines several enablers of future manufacturing competitiveness, which will trigger industrial growth in view of the trends that are influencing today's global market situation. Both, organisational and technological features are analysed in order to understand how they could contribute to an increase of enterprise competitiveness. Especially, the AM-technology and the DMS-concept are highlighted by UNIDO as important enabler of current and future innovation policies.

The dynamism of global acting enterprises is strongly characterised by the implementation of new technologies and the introduction of new organisational forms. The previously mentioned technological-organisational typologies of innovation are the object of numerous studies performed by researchers. The former affects the technological system of manufacturing enterprises through changes of the operational system and the latter shapes the managerial organisation and coordination of production units (Camisón and Villar-López, 2014). According to the Organization for Economic Cooperation and Development (OECD), the technological process innovation refers to 'the adoption of technologically new or significantly improved production methods, including methods of product delivery' (OECD, 2005).

The term distributed manufacturing (DM) indicates a new concept of manufacturing that includes the transition from geographically centralised to decentralised organisations of manufacturing, particularly with regard to location and scale (He and Xu, 2015). Srari et al. (2016) define DM as the 'ability to personalize product manufacturing at multiple scales and locations, be it at the point of consumption sale, or within production sites that exploit local resources, exemplified by enhanced user participation across product design, fabrication and supply, and typically enabled by digitalization and new production technologies.' The need to return to small-scale and local manufacturing is justified by economic, social and environmental factors that impact positively on national and corporate landscapes (Rauch et al., 2016). Even though DM is not intended as the only solution to environmental protection and resource conservation issues, it takes a clear step forward in the improvement of ecological sustainability (Zanetti et al., 2015; Rauch et al., 2016).

A technology which has become the focus of today's manufacturing enterprises and promises enormous benefits in efficiency and flexibility regarding customer individual products is additive manufacturing. Gibson et al. (2010) explain AM based on a procedure with eight steps: The first step consists of the conceptualisation of the part, which is designed with the support of a computer-aided drawing (CAD) software. It is important to convert the generated file into a stereo-lithographic (STL) document, which is transferred and manipulated according to machine requirements. After the adjustment of the STL-file, the AM-equipment is regulated to obtain the optimal setup. The production process can then be launched. Depending on the utilised material quality

and the elaboration accuracy of the used machine, the produced object has to be cleaned and processed by hand or with other machines. The last step is composed of the application of the created 3D-object. AM can be further subdivided into three fields, namely rapid prototyping (RP), rapid manufacturing (RM) and rapid tooling (RT) (Rosochowski and Matuszak, 2000; Hague et al., 2003; Kruth et al., 2007). A further categorisation in AM is possible based on utilised materials. Classical AM-machines utilise principally four different materials, including polymers, metals, composites and ceramics. The polymeric material, and in particular polyamide, is one of the most attractive due to its mechanical properties and costs. RP-machines are typically supplied with polyamide, whose quality depends on the use of the physical prototype, while RT creates tooling equipment made out of polymeric or metallic material. The application, which exploits all four types, is RM (Kruth et al., 2007). The material can be supplied in three forms, including powder, liquid or solid (Kruth et al., 2007; Achillas et al., 2015). Powder, which can be composed of different material types, offers a wide range of compatible technologies including three-dimensional printing, direct metal deposition (DMD), electron beam melting (EBM), selective laser melting (SLM) and selective laser sintering (SLS). The supply of liquid, which consists of polymeric material, occurs for technologies like fused deposition modelling (FDM), ink jet printing (IJP) and stereolithography (SL) (Achillas et al., 2015). Even if enterprises in most instances adopt AM-technologies to create prototypes, other applications, like RM and RT, supported by material-quality and technological advances, become attractive for certain industrial sectors. Automotive, aerospace and medical industries are considered the prime examples of AM-technologies implementation and development. Vehicle constructors that are more and more exposed to time and cost pressures have started introducing AM to achieve significant development savings. Especially during the pre-series production, which is not equipped with a complete tooling, the application of RT optimises and accelerates operations offering suitable bridge tooling. Automotive companies, which operate in the high-end segment dominated by limited series, implement the AM-technologies to deal with the challenge of low-volume production. The aerospace enterprises, which are characterised by similar dynamics, apply AM to govern the geometric and functional complexity of several parts. The advanced technology ensures the production of polymeric or metallic high-performance parts due to the integration of mechanical or internal functionality and the abolition of assembly processes (Wohlers, 2017). The complexity of artefacts plays a central role also in the medical industry and consists in dealing with patient-related or individual challenges (Özceylan et al., 2017). The application of the AM-procedure, which starts with the creation of a digital 3D-data and ends with the production of the physical object, meets the requirements of the customisation process that fulfils patient-needs (Gibson et al., 2010; Özceylan et al., 2017). The range of future application of AM-technologies is vast. While material properties and system costs become more and more efficient, the process speed, the accuracy and the nonlinearity of the created 3D-objects remain the most significant barriers that slow down the application field enlargement (Huang et al., 2015; Dwivedi et al., 2017).

Research Methodology

The applied research methodology is illustrated in Figure 1. The research methodology follows, in its first three steps, the procedure applied in Rauch et al. (2018).

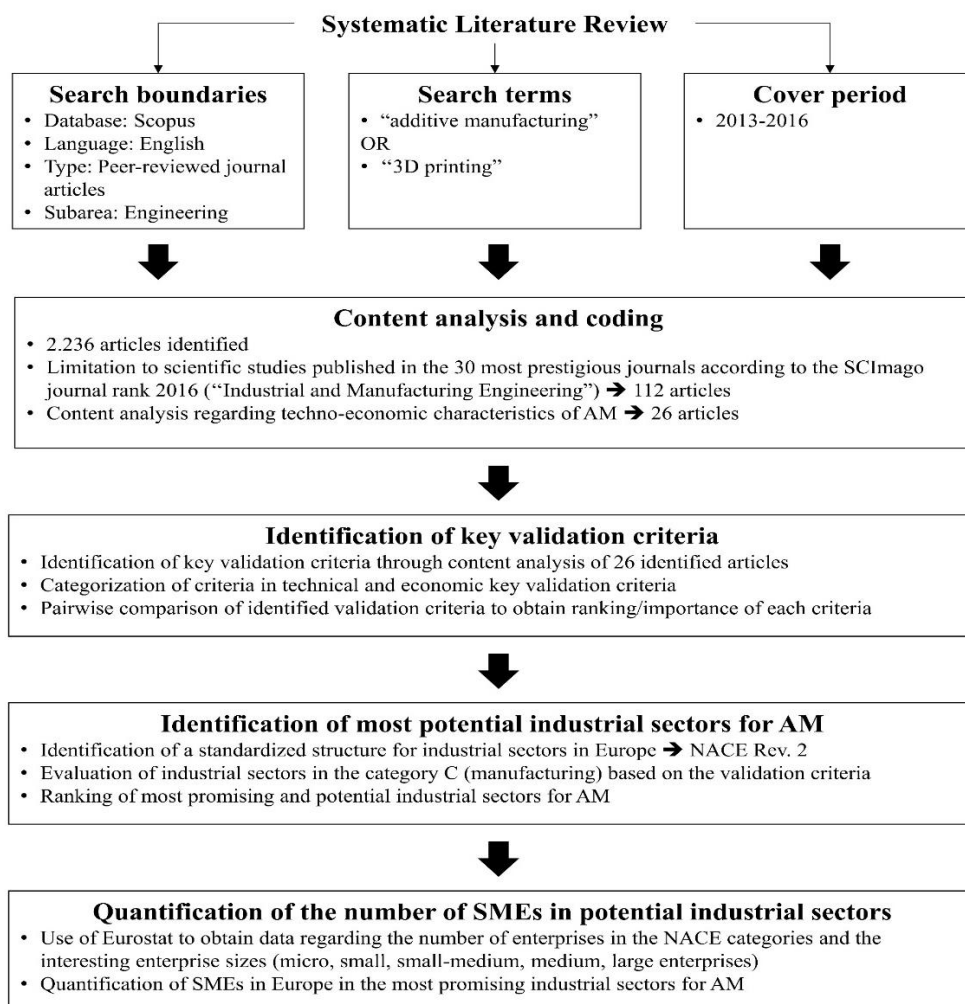


Figure 1. Research methodology.

The first step consists in identifying techno-economic characteristics of AM by performing a systematic literature review. In order to consider a vast amount of the academic literature, the scientific database Scopus was selected and consulted. In the configuration of the database query, different search boundaries as well as search terms and timer periods had to be considered. The search was limited to peer-reviewed scientific journal articles in English language from the subarea “engineering”. The selected search terms were “additive manufacturing” and “3D printing” combined with a Boolean “OR” operation. As this preliminary literature study to determine validation criteria for AM has been conducted in 2017, the authors limited the cover period to the years 2013-2016. The literature search resulted in 2.236 articles. The authors decided to consider only those works from the 30 most prestigious journals according to the SCImago journal rank 2016 in the category “Industrial and Manufacturing Engineering”. This quality-based limitation resulted in a total of 112 articles as a basis for a subsequent content analysis of the scientific works.

In the second step, the research team defined adequate validation criteria to assess the suitability of industrial sectors for AM. Based on the previous content analysis, a total of 14 techno-economic validation criteria could be identified. The research team used a pairwise comparison as methodology to identify the importance of each criterion and to derive a final ranking.

In a third step, the research team identified a suitable structure for the classification of industrial sectors in European enterprises. In Europe, industrial sectors are codified by the European Community using the NACE categories. The notion NACE is derived from the French “Nomenclature statistique des Activités économiques dans la Communauté Européenne” This structure has been evolved and utilised since 1970 to categorise economic activities in Europe. Several revisions performed in the past led to

the formation of the, as used in this study, statistical classification, namely the NACE Rev. 2, which has been valid since 2008. As part of an integrated system of statistical classifications, NACE guarantees international validity and comparability with other statistical domains. Based on a solid structure, it offers a reference framework for organising a wide spectrum of statistical data belonging to various economic activities (Eurostat, 2019). The research team assessed the industrial sectors from category C (manufacturing) in NACE Rev. 2 using the previously defined validation criteria for AM. Based on this evaluation, the research team could derive a ranking of the most promising and potential industry sectors for the application of AM.

In a fourth step, the research team investigated the potential of AM for European SMEs based on the previously identified most promising industry sectors. For this study, the research team consulted the EUROSTAT database (Eurostat, 2018) as source for information in obtaining relevant data from 2016. Using this data, the potential of AM for European SMEs could be quantified by providing the total number of SME enterprises in potential industry sectors for AM.

RESULTS

Definition of key criteria for validating the potential of AM in industrial applications

Based on the content analysis of the systematic literature review, the following seven technological and seven economic validation criteria were identified (Table 1). These validation criteria were identified by reading the prior identified scientific literature and extracting the technological and economic characteristics of suitable and not suitable parts for AM. Analysing and interpreting those characteristics, the research team then defined appropriate AM validation criteria. Table 1 gives also an overview of how to interpret the 14 validation criteria, describing exemplary parts with suitable and not suitable characteristics for applying AM as manufacturing technology.

Table 1. Identified techno-economic validation criteria for AM.

No.	Suitable parts	Not suitable parts	AM validation criteria
Technological characteristics			
1	High functional complexity	Low functional complexity	Functional complexity (FC)
2	High geometric complexity	Simple geometries	Geometric complexity (GC)
3	Use of materials inside the range of AM materials	Use of materials out of the range of AM materials	Materials used (MU)
4	Multi-material parts need additional assembly if fabricated with conventional manufacturing technologies	Single-material parts need no additional assembly if fabricated with conventional manufacturing technologies	Multi-material parts (MMP)
5	Low need for mechanical resistance	Need for high mechanical resistance	Mechanical resistance (MR)
6	Low to medium precision parts (surface, shape and dimension)	High precision parts (surface, shape and dimension)	Precision of parts (PP)
7	Small scale parts	Large scale parts	Size and dimension (SD)
Economic characteristics			
8	High individualisation grade	High standardisation grade	Individualisation (I)
9	Cost-sensitive storage of the part (lower storage through production-on-demand with AM)	No cost-sensitive storage of the part (and thus suitable for make to stock)	Cost-sensitive storage (CSS)
10	Parts with long cycle times	Parts with short cycle times	Cycle time (CT)
11	Frequent design changes	Robust design without frequent design changes	Frequency of design changes (FDC)
12	Low requirements of intellectual property protection	High requirements of intellectual property protection	Intellectual property protection (IPP)
13	Single-unit and small series production	Large series and mass production	Production lot size (PLS)
14	Conventional manufacturing technologies require cost-intensive tooling	Conventional manufacturing technologies do not require cost-intensive tooling	Tooling Costs (TC)

The methodology applied to define the relevance of the determined key validation criteria is a pairwise comparison. This tool plays an essential role in the multi-attribute decision-making (MADM) process (Kahraman et al., 2004). Objects or so-called "stimuli" are organised in pairs and taken into consideration by a board of judges. The acting judges of the research team expressed clear priorities that allowed to determine a precise ranking of the identified key validation criteria, in which two parameters cannot achieve the same degree of importance. It has to be noted that the evaluation process performed through the pairwise comparison contains a certain grade of subjectivity that was limited in this study by engaging three members of the research team to act as judges and, therefore, to objectify opinions and decisions made. All three judges are experienced in the theory and practice of AM. To conduct the pairwise comparison a so-called pairwise comparison matrix (PCM) was used. The represented $n \times n$ matrix in Equation 1 illustrates the concept of the PCM (Ayağ and Özdemir, 2012).

$$= \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ 1/a_{12} & 1 & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{n1} & 1/a_{n2} & \dots & 1 \end{bmatrix} \quad (1)$$

where $a_{ii} = 1$ and $a_{ij} = \frac{1}{a_{ji}}$ for $i, j = 1, 2, \dots, n$.

The judges are allowed to indicate clear preferences utilising the value 1, if the examined criterion is more relevant, and 0, if the considered criterion is less relevant. By summing up all the values, the final scoring, which permits to create the ranking, is determined. The examined validation criteria are presented in Table 2 in the order of the ranking results.

Table 2. Pairwise comparison to define the ranking of the validation criteria

Criteria	I	SD	CT	PLS	GC	FDC	FC	IPP	TC	MMP	PP	CSS	MU	MR	Score	%
I		1	1	1	1	1	1	1	1	1	1	1	1	1	13	93%
SD	0		1	1	1	1	1	1	1	1	1	1	1	1	12	86%
CT	0	0		1	1	1	1	1	1	1	1	1	1	1	11	79%
PLS	0	0	0		1	1	1	1	1	1	1	1	1	1	10	71%
GC	0	0	0	0		1	1	1	1	1	1	1	1	1	9	64%
FDC	0	0	0	0	0		1	1	1	1	1	1	1	1	8	57%
FC	0	0	0	0	0	0		1	1	1	1	1	1	1	7	50%
IPP	0	0	0	0	0	0	0		1	1	1	1	1	1	6	43%
TC	0	0	0	0	0	0	0	0		1	1	1	1	1	5	36%
MMP	0	0	0	0	0	0	0	0	0		1	1	1	1	4	29%
PP	0	0	0	0	0	0	0	0	0	0		1	1	1	3	21%
CSS	0	0	0	0	0	0	0	0	0	0	0		1	1	2	14%
MU	0	0	0	0	0	0	0	0	0	0	0	0		1	1	7%
MR	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0%

Identification of potential industrial sectors

For the identification of the most promising industrial sectors, the research team used NACE Rev. 2 as standardised structure for industrial sector categories. In total, 94 industrial sectors are associated in NACE Rev. 2 to the section C (manufacturing) which was used as basis for the evaluation of the potential of AM in industrial sectors in Europe. The 94 classes were evaluated by the research team utilising a 10-point rating system (where 0 means the validation criteria are not fulfilled, 10 means the validation criteria are fully fulfilled). After discussions with external experts, the research team, consisting of three persons, engaged two team members to evaluate the industrial classes independently from the other. After this, the third person calculated the average of the evaluations and acted as decision-maker in case of not clearly equal scores. The evaluation is weighted according to the previously defined importance/rank of each evaluation criterion based on pairwise comparison (see % in Table 2). The final score

of each of the 94 classes is calculated through the sum of the values for each validation criteria. The detailed evaluation of all 94 classes is illustrated in Table 3.

Table 3. Results of the evaluation of European manufacturing industry sectors regarding the potential of AM (NACE Rev. 2 - 94 subcategories of section C manufacturing).

Cat.	NACE (Rev. 2) Manufacturing Sector	I	SD	CT	PLS	GC	FDC	PP	IPP	TC	MMP	PP	CSS	MU	MR	Total Score
14.19	Manufacture of other wearing apparel and accessories	9	5	3	6	8	10	2	3	0	6	3	2	2	2	35,21
15.12	Manufacture of luggage, handbags and the like, saddlery and harness	1	4	1	3	1	1	2	7	0	1	3	2	7	6	14,21
15.20	Manufacture of footwear	8	8	6	3	6	9	3	2	3	7	7	1	2	5	37,36
22.21	Manufacture of plastic plates, sheets, tubes and profiles	1	1	2	2	2	1	1	9	7	7	4	2	7	3	17,14
22.22	Manufacture of plastic packing goods	5	5	1	1	6	5	1	10	0	6	8	0	8	3	25,93
22.23	Manufacture of builders' ware of plastic	0	7	1	1	4	1	2	10	4	5	8	0	8	4	21,07
22.29	Manufacture of other plastic products	3	4	2	2	5	1	3	10	0	4	7	1	8	3	22,14
23.31	Manufacture of ceramic tiles and flags	5	8	2	5	2	2	0	9	5	0	8	1	4	2	26,86
23.32	Manufacture of bricks, tiles and construction products, in baked clay	0	5	2	2	1	0	1	10	4	0	8	1	4	2	16,29
23.41	Manufacture of ceramic household and ornamental articles	7	7	2	4	7	6	1	2	4	0	4	2	4	7	29,07
23.42	Manufacture of ceramic sanitary fixtures	5	3	2	4	2	2	1	3	4	0	8	1	4	3	19,43
23.43	Manufacture of ceramic insulators and insulating fittings	1	5	2	3	1	0	1	9	0	1	5	1	4	4	15,71
23.44	Manufacture of other technical ceramic products	4	7	2	3	2	2	4	8	3	1	4	1	4	2	23,93
23.49	Manufacture of other ceramic products	5	5	2	4	2	2	2	5	3	0	7	1	4	7	21,93
24.20	Manufacture of tubes, pipes, hollow profiles and related fittings, of steel	1	1	3	1	1	0	2	10	3	2	8	1	7	2	14,79
25.11	Manufacture of metal structures and parts of structures	5	2	7	5	5	2	1	8	3	3	8	1	8	2	28,07
25.12	Manufacture of doors and windows of metal	6	1	5	2	2	3	2	7	3	3	7	1	7	2	22,86
25.21	Manufacture of central heating radiators and boilers	1	2	8	2	1	1	6	4	2	5	8	1	7	2	20,79
25.29	Manufacture of other tanks, reservoirs and containers of metal	1	1	5	1	1	0	0	10	2	4	8	1	7	1	15,57
25.30	Manufacture of steam generators, except central heating hot water boilers	2	1	7	1	2	1	5	4	2	4	8	1	7	1	19,21
25.40	Manufacture of weapons and ammunition	3	5	5	3	6	1	7	1	8	7	1	1	4	1	27,00
25.50	Forging, pressing, stamping and roll-forming of metal; powder metallurgy	10	5	5	8	8	1	2	1	4	0	1	1	7	1	32,64
25.61	Treatment and coating of metals	1	5	3	1	2	1	0	10	1	5	6	0	8	5	18,07
25.62	Machining	5	5	2	6	3	2	4	8	8	1	2	1	7	2	27,50
25.71	Manufacture of cutlery	5	8	1	2	3	3	1	4	2	1	7	3	7	6	23,00
25.72	Manufacture of locks and hinges	5	8	4	3	2	2	8	1	5	3	2	1	7	1	27,36
25.73	Manufacture of tools	5	5	5	3	5	3	4	5	5	6	3	3	4	3	28,93
25.91	Manufacture of steel drums and similar containers	1	2	2	1	1	1	1	10	2	1	9	1	8	7	14,57
25.92	Manufacture of light metal packaging	1	2	2	3	1	1	1	10	1	1	9	2	9	7	15,86
25.93	Manufacture of wire products, chain and springs	1	5	1	1	2	1	5	8	5	1	8	2	8	2	19,14
25.94	Manufacture of fasteners and screw machine products	1	5	2	1	5	2	2	7	2	3	3	1	5	0	18,57
25.99	Manufacture of other fabricated metal products n.e.c.	4	5	5	4	6	5	5	5	6	4	3	4	3	2	30,86
26.20	Manufacture of computers and peripheral equipment	5	7	2	5	4	6	3	7	2	6	5	2	6	4	30,50
26.30	Manufacture of communication equipment	4	8	5	3	4	7	2	3	3	7	5	3	5	3	30,43
26.40	Manufacture of consumer electronics	2	5	3	2	4	4	3	5	2	8	7	1	7	4	23,57
26.51	Manufacture of instruments and appliances for measuring, testing and navigation	1	7	3	5	1	0	8	2	7	6	0	1	5	5	23,07
26.52	Manufacture of watches and clocks	2	8	7	3	5	2	9	1	7	6	0	1	3	1	30,21
26.60	Manufacture of irradiation, electromedical and electrotherapeutic equipment	0	1	8	8	2	1	7	1	7	6	0	0	5	3	23,21
27.11	Manufacture of electric motors, generators and transformers	1	5	3	2	4	1	7	8	2	3	3	1	7	3	21,93
27.12	Manufacture of electricity distribution and control apparatus	0	1	1	1	2	0	1	10	2	7	2	1	8	1	12,29
27.40	Manufacture of electric lighting equipment	0	1	1	1	3	0	2	10	1	6	3	1	8	2	13,00
27.51	Manufacture of electric domestic appliances	1	5	2	1	4	2	3	8	1	7	4	1	7	7	20,00
27.52	Manufacture of non-electric domestic appliances	0	5	1	1	3	1	3	9	1	6	8	1	6	8	18,00
27.90	Manufacture of other electrical equipment	1	3	1	1	2	1	2	9	1	6	6	1	7	5	15,71
28.11	Manufacture of engines and turbines, except aircraft, vehicle and cycle engines	1	2	7	2	4	1	7	2	6	7	1	2	6	1	22,14
28.12	Manufacture of fluid power equipment	1	3	7	3	4	1	7	5	5	7	1	1	6	1	24,50
28.13	Manufacture of other pumps and compressors	1	2	7	2	2	1	8	6	2	4	1	1	7	1	20,71
28.14	Manufacture of other taps and valves	0	6	5	1	5	0	6	8	2	7	2	1	7	1	23,21
28.15	Manufacture of bearings, gears, gearing and driving elements	1	7	8	2	7	0	7	8	2	1	1	1	7	1	27,93
28.21	Manufacture of ovens, furnaces and furnace burners	1	2	8	2	3	1	5	7	2	5	7	1	6	2	22,57
28.22	Manufacture of lifting and handling equipment	2	1	8	3	2	1	6	6	1	6	5	1	7	1	22,36
28.23	Manufacture of office machinery and equipment (except computers and peripheral equipment)	1	1	6	1	1	0	7	3	1	6	1	2	6	4	15,64
28.24	Manufacture of power-driven hand tools	1	7	6	2	6	1	5	8	2	7	5	1	8	3	27,93
28.25	Manufacture of non-domestic cooling and ventilation equipment	0	1	5	4	1	1	2	8	2	5	6	1	6	6	17,29
28.29	Manufacture of other general-purpose machinery n.e.c.	1	4	7	2	3	1	5	6	1	5	7	1	6	3	22,71
28.30	Manufacture of agricultural and forestry machinery	2	2	7	4	5	1	7	3	2	6	3	1	6	1	24,14
28.41	Manufacture of metal forming machinery	1	1	7	3	2	0	5	3	2	5	2	1	4	1	17,50
28.49	Manufacture of other machine tools	2	7	5	3	5	1	5	7	3	5	1	1	2	1	26,21
28.91	Manufacture of machinery for metallurgy	0	1	8	4	3	0	5	7	8	4	3	1	5	2	22,57
28.92	Manufacture of machinery for mining, quarrying and construction	1	0	8	3	4	1	6	5	6	4	2	2	4	1	21,93
28.93	Manufacture of machinery for food, beverage and tobacco processing	4	3	6	6	3	1	7	2	2	5	2	1	3	3	25,07
28.94	Manufacture of machinery for textile, apparel and leather production	3	2	7	5	3	1	6	3	2	4	2	1	4	3	23,07
28.95	Manufacture of machinery for paper and paperboard production	2	2	7	6	3	1	6	2	3	3	2	1	3	3	22,43
28.96	Manufacture of plastics and rubber machinery	2	2	7	6	3	1	7	2	2	3	2	1	3	2	22,57
28.99	Manufacture of other special-purpose machinery n.e.c.	2	2	7	5	3	1	6	3	2	4	2	1	3	3	22,07
29.10	Manufacture of motor vehicles	6	5	7	3	6	7	7	5	3	7	5	3	7	3	36,07
29.20	Manufacture of bodies (coachwork) for motor vehicles; manufacture of trailers and semi-trailers	4	2	5	3	8	8	7	5	4	3	2	1	4	3	30,00
29.31	Manufacture of electrical and electronic equipment for motor vehicles	1	4	1	2	1	1	2	2	1	4	5	1	6	2	12,79
29.32	Manufacture of other parts and accessories for motor vehicles	3	3	4	2	5	7	6	5	2	3	3	1	5	3	25,00
30.11	Building of ships and floating structures	2	1	5	4	6	5	4	4	5	4	4	2	3	2	24,21
30.12	Building of pleasure and sporting boats	5	2	4	5	6	4	5	6	4	3	5	1	4	3	28,07
30.20	Manufacture of railway locomotives and rolling stock	2	6	8	4	5	2	4	5	3	6	2	1	5	1	28,36
30.30	Manufacture of air and spacecraft and related machinery	7	6	9	8	9	2	9	2	3	7	2	1	6	1	40,79
30.40	Manufacture of military fighting vehicles	3	5	7	3	6	2	7	1	6	5	2	1	4	0	28,07
30.91	Manufacture of motorcycles	6	4	6	3	6	7	7	5	3	6	5	2	6	3	33,93
30.92	Manufacture of bicycles and invalid carriages	8	6	4	4	7	4	4	3	4	7	6	1	3	2	33,71
30.99	Manufacture of other transport equipment n.e.c.	2	5	7	5	7	2	6	3	3	4	2	1	3	1	28,14
31.01	Manufacture of office and shop furniture	3	8	1	1	2	5	3	8	3	5	8	1	9	8	25,21
31.02	Manufacture of kitchen furniture	9	3	5	5	1	4	4	3	3	1	5	7	3	2	28,50
31.09	Manufacture of other furniture	8	2	5	4	1	5	2	3	1	6	7	3	2	4	25,86
32.12	Manufacture of jewellery and related articles	9	8	7	8	8	5	1	1	6	7	3	5	2	8	41,00
32.13	Manufacture of imitation jewellery and related articles	9	8	7	6	8	5	1	4	6	8	4	1	5	8	41,00
32.20	Manufacture of musical instruments	3	3	8	6	8	1	9	3	6	7	2	3	2	5	32,57
32.30	Manufacture of sports goods	8	8	6	2	4	7	8	1	6	8	3	3	2	2	37,07
32.40	Manufacture of games and toys	1	7	5	2	3	5	4	2	4	8	7	3	3	6	25,79
32.50	Manufacture of medical and dental instruments and supplies	10	10	7	9	8	3	7	10	5	8	2	1	5	1	49,43
33.11	Repair of fabricated metal products	7	7	3	3	8	0	6	3	7	7	2	2	7	2	32,14
33.12	Repair of machinery	6	9	4	3	8	0	7	2	5	5	2	5	7	1	32,93
33.13	Repair of electronic and optical equipment	1	8	2	2	3	0	5	1	1	5	3	1	3	8	18,43
33.14	Repair of electrical equipment	1	8	2	2	3	0	4	2	1	5	3	1	4	8	18,43
33.15	Repair and maintenance of ships and boats	1	5	3	6	5	0	6	7	4	5	5	2	5	2	25,64
33.16	Repair and maintenance of aircraft and spacecraft	2	9	5	9	9	0	9	2	8	8	1	5	6	1	37,57
33.17	Repair and maintenance of other transport equipment	2	8	6	7	6	0	7	2	3	5	2	4	5	1	30,50
33.19	Repair of other equipment	2	7	5	7	6	0	8	3	3	5	3	4	5	2	30,00

Based on the evaluation of the NACE Rev. 2 industrial sectors of the section manufacturing, (see Table 3) the research team deduced a graph showing the ranking of the 20 most promising industrial sectors for AM (Figure 2).

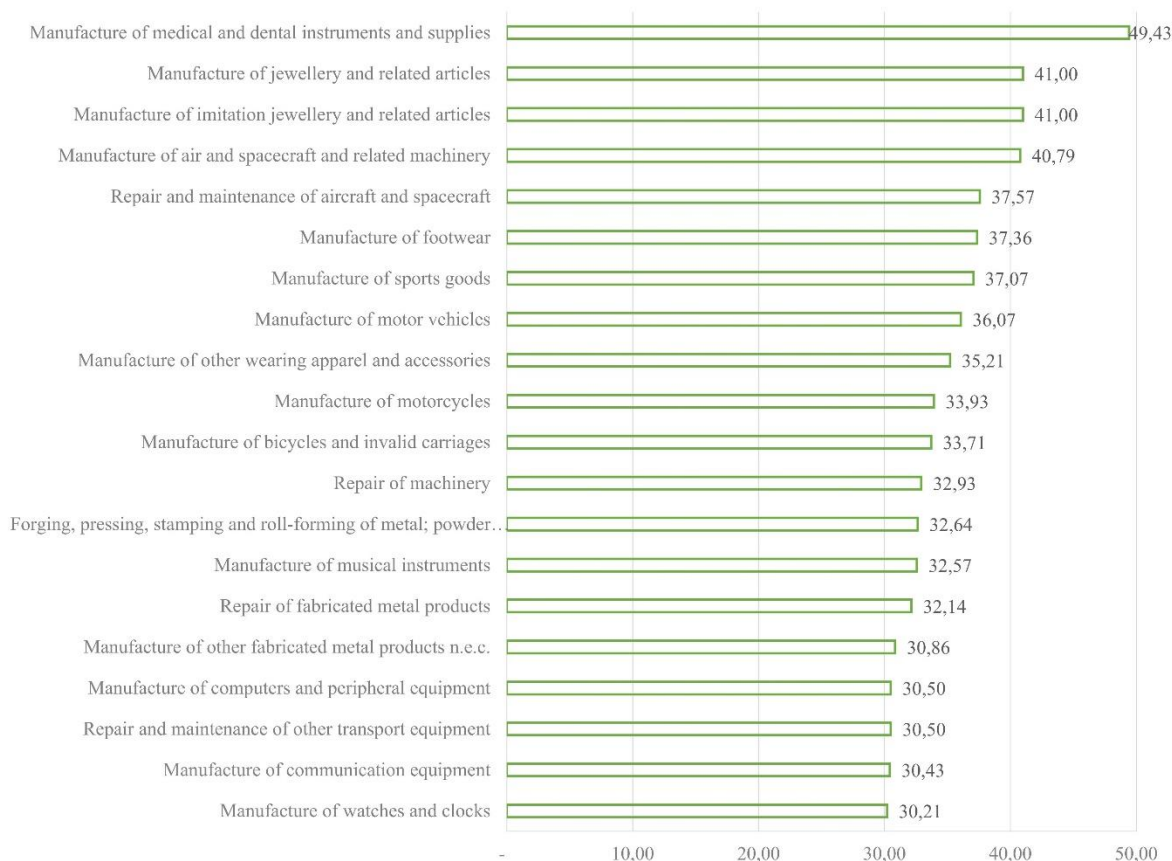


Figure 2. Top 20 industrial manufacturing sectors for the use of AM.

In this ranking, one industrial sector in particular, “manufacturing of medical and dental instruments and supplies”, resulted to be especially interesting for AM application having a total score of 49.43. Another three interesting industrial sectors with high values between 40.79 and 41.00 are related to the manufacturing of jewellery (genuine and imitated) and to manufacturing of aircraft and spacecraft parts. Another cluster with medium scores between 35.21 and 37.57 is related to repair and maintenance of the aforementioned aircraft and spacecraft parts, manufacturing of footwear and sports goods, manufacturing of motor vehicles and manufacturing of wearing apparel and other accessories. A cluster with medium to low scores can be identified between values of 32.14 and 33.93 with manufacturing of motorcycles and bicycles, repair of machinery, forging/pressing/stamping manufactures, manufacturing of music instruments and the repair of metal products. The lowest scores in this Top 20 (with values from 30.21 to 30.86) were achieved in sectors like manufacturing of metal products or computers, repair and maintenance of transport equipment, manufacturing of communication equipment and manufacturing of watches and clocks.

Importance of SMEs in potential industrial sectors for AM

Having the information about highly promising industrial sectors in the European manufacturing economy can be used in a later step to identify the potential of SMEs in the adoption of AM as manufacturing technology. In order to define and to quantify the potential of AM in European SMEs, the research team used the European statistical database EUROSTAT to retrieve information about the number of companies in the above identified potential NACE sectors and their subdivision into micro enterprises, SMEs and large enterprises. As the granularity of data in EUROSTAT allowed a more

detailed analysis, the research team used the following categorisation of the company size:

- 0-9 employees: micro enterprises;
- 10-19 employees: small enterprises (SME);
- 20-49 employees: small-medium enterprises (SME);
- 50-249 employees: medium enterprises (SME);
- 250 employees and more: large enterprises.

Consulting the EUROSTAT database (Eurostat, 2018), the research team could retrieve all the information needed to conduct the study. The focus in this study is on SMEs and, therefore, those company sizes between 10 and 249 employees (small, small-medium and medium). Therefore, in Table 4 the values of this company sizes are highlighted taking into account only those categories with a score of over 35.00 and, therefore, medium to high potential to adopt AM. In Table 4, we show the values of the EU-28 (therefore, the 28 countries associated in the European Union) as well as for two exemplary countries (Italy and Austria).

In Table 4, the numbers of 32.12 (genuine jewellery) and 32.13 (imitated jewellery) are combined in category 32.1 as no numbers for the next category level could be retrieved in Eurostat. The added subcategory 32.11 is "striking of coins", thus the use of the upper level category 32.1 shouldn't result in a large deviation and was, therefore, included in the study. For the categories 33.16 (repair and maintenance of aircraft and spacecraft) and 14.19 (manufacture of other wearing apparel and accessories), no specific data could be retrieved from Eurostat database for this level of detail. Therefore, neither category could be included in the study in Table 4.

Table 4. Potential of AM in European SMEs – number of enterprises in the most promising industrial manufacturing sectors (n.a. means not available data).

Cat.	NACE category	Country	Total	Company size by number of employees				
				0-9	10-19	20-49	50-249	250 and more
32.50	Manufacture of medical and dental instruments and supplies	EU 28	65.05	58.44	3.80	1.65	941	219
		Italy	16.76	16.19	311	155	88	17
		Austria	850	686	104	38	18	4
32.1	Manufacture of jewellery, bijouterie and related articles	EU 28	43.19	41.45	1158	383	173	18
		Italy	7.70	7.06	437	134	58	6
		Austria	431	411	11	6		
30.30	Manufacture of air and spacecraft and related machinery	EU 28	2.06	1.31	166	183	236	163
		Italy	187	102	23	20	2	16
		Austria	18	9	2	1	5	1
15.20	Manufacture of footwear	EU 28	20.20	14.72	2512	1936	n.a.	n.a.
		Italy	8.02	6.02	1182	611	194	19
		Austria	87	63	7	7	10	0
32.30	Manufacture of sports goods	EU 28	5.00	4.26	297	221	194	22
		Italy	634	518	71	35	n.a.	n.a.
		Austria	81	53	8	8	8	4
29.10	Manufacture of motor vehicles	EU 28	2.59	2.01	139	123	157	159
		Italy	124	80	10	9	15	10
		Austria	12	-	1	1	3	7

DISCUSSION

With the research approach in this work we wanted to investigate the potential of the application of AM. For this purpose, key validation criteria were defined on the basis of a literature search and used to identify those industrial sectors that show the greatest potential for AM. In order to break the result down to a practical level and to quantify it, a data-based investigation was carried out on how many SMEs exist in Europe in these potential industrial sectors.

Using the number of SMEs per potential industry sector to quantify the overall potential of AM in European SMEs, it seems that the NACE category 32.50 (manufacturing of medical and dental instruments) with a total of 6,395 SMEs, the category 15.20 (manufacturing of footwear) with more than 5,000 SMEs and the category 32.10 (manufacturing of jewellery, bijouterie) with a total of 1,714 SMEs, are the most promising and potential industry categories for European SMEs. The sum of all other industry sectors in category 30.30 (manufacturing of air and spacecraft parts), 32.30 (manufacturing of sports goods) and 29.10 (manufacturing of motor vehicles) represent a total of another 1,716 SMEs. In total, AM could be a highly interesting manufacturing alternative for almost 15,000 SMEs in Europe, where 8,080 (~54%) are small enterprises with 10-19 employees 4,492 (~30%) are small-medium enterprises with 20-49 employees and almost 2,400 (~16%) are medium-sized enterprises with 50-249 employees.

Table 5 summarizes these most potential industrial sectors giving also an overview of practical examples how AM could be used, and which kind of products are already produced with AM technologies based on references from scientific and managerial literature.

Table 5. Examples of AM in the most promising industrial sectors.

Cat.	NACE category	#SMEs in EU 28	Examples	References
32.50	Manufacture of medical and dental instruments and supplies	>6.000	AM for dental implants made of titanium; On-demand production of surgical kits; AM of biomaterials in the medical sector	Tunchel et al. (2016); Kondor et al. (2013); Touri et al. (2019)
15.20	Manufacture of footwear	>5.000	AM for personalized insoles; Small scale footwear enterprises	Salles et al. (2013); Gebre-Egziabher (2007)
32.1	Manufacture of jewellery, bijouterie and related articles	>1.700	AM for production of customized jewellery; Functional jewellery	Cooper (2016) Matos et al. (2017)
32.30	Manufacture of sports goods	>700	3D printed sports helmets; Carbon-fibre 3D printing for bikes	Raykar et al. (2020); Nickels (2019)
30.30	Manufacture of air and spacecraft and related machinery	>500	Integrated aircraft structures; Complex parts in aerospace	Türk et al. (2016); Kumar et al. (2017)
29.10	Manufacture of motor vehicles	>400	Production of spare parts	Blennow et al. (2018)

The results of this work have important implications for academics as well as for practitioners. Scientists are given an overview of potential areas of application for AM, enabling them to carry out applied research in a much more targeted manner. In addition, scientists around the world can transfer the methodology applied in this work to country databases other than Europe and thus investigate the potential in other areas as well. Scientists can concentrate their research on those areas that have a high potential and, by means of case study research with best practice examples, help to ensure that research results are increasingly transferred into practice and can thus be exploited by SMEs. At the other side, practitioners from SMEs get a clear overview of whether their company falls into these potential categories and thus whether the use of AM could represent a new business model or a new interesting technology.

Although the results are promising we want to note also possible limitations of this study. The study was based on data from Italy, Austria and the EU-28 countries.

Although the results from this database are highly representative for Europe, they may not be transferable to all other economies. As mentioned above, similar studies will therefore have to be applied to other countries in the future, both industrialised and developing countries, and the interrelationships and differences analysed.

CONCLUSION

AM is considered a breakthrough technology that will revolutionise traditional manufacturing strategies. The initial hype about the technology has now gradually calmed down and the technology has matured strongly in recent years. In the meantime AM has been successfully applied in some niche markets, but there is still no satisfactory analysis of where AM has the most potential. In addition, there has been no satisfactory study to date which has also highlighted the potential of AM in SMEs. In the present study, an attempt was made to close this gap by deriving validation criteria for the successful use of AM in manufacturing companies on the basis of a literature analysis. Based on these criteria, 94 NACE industrial sectors were evaluated and a list of the top 20 industrial sectors for the use of AM was determined. Starting from those sectors with the highest potential, Eurostat data were used to determine how many SMEs are currently active in these sectors. The result was that AM is currently a highly interesting and attractive technology for around 15,000 European SMEs in the manufacture of medical and dental devices, of air and spacecraft parts, of jewellery, of footwear, of sports goods and of motor vehicles. These findings are extremely important information both for scientists and, especially, for managers from the SME categories concerned, on the basis of which they can make decisions for future investments and further research activities.

As a recommendation, SMEs from the identified industry sectors with a high potential for AM should deal with this topic and include AM in their vision and their business strategy. In addition, policy makers should also provide appropriate funding programs and incentives for this industry sectors e.g. to install first pilot machines or to qualify their employees to use AM technology in the own business structure.

As an outlook for the future, the research team will prepare a similar study for Thailand and for the United States as the research team consists of researchers from Europe, from Thailand and from the United States. The same validation criteria will be applied, but the structure of the industrial sectors and the database for statistical evaluations will be adapted to comparable sources in Thailand and the USA. A comparison of the two studies should show to what extent the results between the three geographical areas differ or overlap. The results of this research will support the research team to define further research activities in order to exploit the potential of SMEs using AM in their production facilities.

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