Why manufacturers adopt additive manufacturing technologies? The role of sustainability

Abstract

Emerging manufacturing technologies affect companies' internal as well as external performances. Hence, a proportionate and purposive choice of the technology will significantly impact the success of a firm. Additive Manufacturing (AM), a leading and impactful technology, is implemented in many industrial sectors for a variety of reasons. It offers huge potential benefits in terms of sustainability perspectives. First, this study aims to identify and to prioritize the determinants of AM adoption. Secondly, the research clarifies the role of sustainability benefits on the decision to adopt and, then, seeks to distinguish the priorities in different application sectors through a multi-stage survey. The results prove a leading impact of economic motives on the decision to adopt, and the auxiliary role of environmental and social sustainability benefits. The findings also indicate that the capability of additive manufacturing for producing almost any complex design is the key determinant of its adoption in all sectors.

Keywords: Additive Manufacturing; Technology adoption; Sustainability; Survey

1. INTRODUCTION

Additive Manufacturing (AM) has attracted the attention of several academic and industrial researchers in the recent years. Researchers argue that AM has several potential benefits for sustainability (e.g. Chen *et al.,* 2015; Ford and Despeisse, 2016) and is considered as a key manufacturing technology in the sustainable society of the future (Huang *et al.,* 2013). From the perspective of economic sustainability, AM allows less resource usage (Ullah *et al.,* 2013) and less operational costs (Weller *et al.,* 2015). As regards environmental sustainability, AM conserves energy (Tang *et al.,* 2016), resources and emissions (Yang and Li, 2018). AM also promises several social impacts, particularly, on the way people consume and companies satisfy the demand (Huang *et al.,* 2013). These potentials have quantified a cost reductions of 170–593 billion US $, to avoid Total Primary Energy Supply (TPES) of 2.54–9.30 exajoules (EJ) and would avoid CO2 emissions by 130.5–525.5 Metric tons (Mt) by 2025 in the markets identified for AM (Gebler *et al.,* 2014).

Pertaining to the domain of application, AM has gone through different phases of evolution from its initiation. Berman (2012) stated three evolutionary phases as respectively the use of the technology for prototyping, for end-usable products, and the time that consumers own AM technology for self-fabrication. However, AM has faced two other evolutionary phases in the recent years in addition to what Berman had recognized in 2012 (*see* figure 1).

The fourth phase of this evolution relates to the opportunities for co-creation. This phase is also known as networked manufacturing or cloud manufacturing (Rayna *et al.,* 2015). The emerging online 3D printing platforms provide a marketplace allowing participants to share their capacities for value creation. In the setting of cloud manufacturing, designers present design files or are being involved in the design modifications and optimizations, owners of the physical equipment (like AM machines) share their manufacturing capacities, and service providers are available for coordination and service management. In addition, companies can benefit from involving their customers in any stage of the product development process since the design modifications become easier thanks to the nature of AM. Therefore, AM can cause moving from a manufacturing-centric to rather customer-centric business models (Bogers *et al.,* 2016). Suppliers are no longer the only source for the creation of value-added, while consumers are being involved in value creation and therefore act as the so-called *prosumers*. Thus, the pattern of consumption has been subjected to a big shift (Chen *et al.,* 2015) where the consumers are being either producer or being involved in design or fabrication.

Although AM technologies cannot currently compete with conventional manufacturing for mass production, some industrial cases have shown the capability of AM for serving larger production volumes. These evidences promise the fifth phase of its evolution. For instance, GE Aviation could efficiently produce more than 100,000 jet engine's fuel nozzle using AM technologies (GE, 2015). GE could print this part with 25 percent lighter weight and as much as five times more durable than what was produced using conventional manufacturing (Khorram Niaki and Nonino, 2018). AM allowed the nozzle that used to be assembled from 20 separate cast parts, to be fabricated in one piece. GE declared that this would cut the cost of manufacturing by 75% (D'Aveni, 2015), yielded significant savings up to $3 million per aircraft per year (Rao, 2016). In addition, Airbus reported that they have used 1000 additively manufactured components in their A350 XWB commercial jetliner (Stratasys, 2015). Moreover, several customized medical parts are being mass-produced using AM technologies. More than 10 million hearing aid shells, around 50 million dental bridges, copings and crowns have already been made using AM technologies (Oettmeier and Hofmann, 2017). Aforementioned cases promise the fifth evolutionary phase of AM, termed as mass-production of special components. These are special components because their manufacturers benefited from the unique advantages of AM and employed the principles arisen from Design for Additive Manufacturing (DFAM) guidelines (Yang and Zhao, 2015).

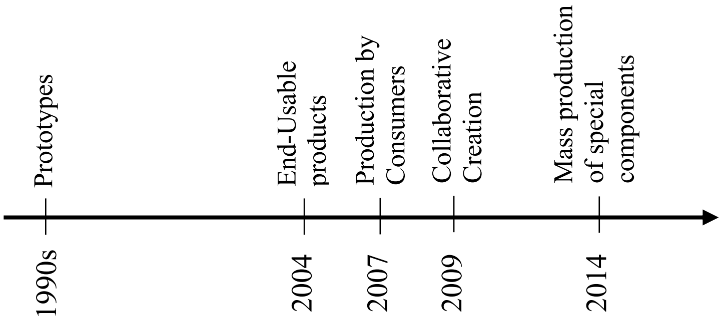

Fig. 1. Timeline of AM technological evolution

According to Khorram Niaki and Nonino (2017a), the literature on the AM management consists of eight clusters of articles discussing the topic from different viewpoints and one concerns AM technology adoption. The majority of articles belonging to this cluster conceptually investigated the technology adoption problems, while there are a few empirical studies attempting to face the factors affecting AM adoption and, to our knowledge, there is not a study trying to understand the driving role of sustainability benefits.

Nowadays the diffusion of AM technology is considerably growing and the public sector continues to encourage adoption of this technology (Jiang *et al.,* 2017). Therefore, there is the necessity of an in-depth study that empirically analyzes the reasons of the preference of AM technologies over the conventional manufacturing. Moreover, as stated before, the literature demonstrates the huge potential benefits of AM for sustainability (e.g. Ford and Despeisse, 2016) and its key role in the green society of the future (Huang *et al.,* 2013). However, there are a few studies to clarify to what extent these potential benefits have been realized in practice. To the best of our knowledge, there are also few studies to investigate the reasons and determinants of AM technology adoption; however, the existing studies (e.g. Schniederjans, 2017; Oettmeier and Hofmann, 2017) analyzed the determinants through interdisciplinary factors at the interface of behavioral science and diffusion of innovation researches.

This research seeks to provide an empirical assessment from the standpoint of actual manufacturing practitioners to understand what factors drive AM adoption. The special emphasis is to understand the role of sustainability benefits on the adoption of AM technology. In fact, the findings depict the most advantageous features of AM that can attract more manufacturers to implement the technology. Moreover, since each application sector may have its own requirements and according to call for further studies on comparative studies of different application sectors suggested by Ford and Despeisse (2016), this study also attempts to identify their unique priorities to adopt AM technologies. Consequently, our research aims at answering the following three research questions: *Why do manufacturers adopt AM technologies? Which is the role of sustainability benefits on the decision to adopt AM?* and *Which are the key determinants of different application sectors for adopting AM technologies?*

The paper is structured as follows. Section 2 analyzes the recent literature on the management of AM technology, particularly from the sustainability perspectives. This is followed by the review of current limitations on the widespread diffusion and then previous researches identifying the determinants of AM adoption. Section 3 describes the methodology and the research sample. Section 4 analyzes gathered data and discusses the findings of the research. The last section concludes the article and outlines the research limitations, academic and managerial implications, and future research suggestions.

2. LITERATURE REVIEW

AM technologies offers huge benefits in terms of the sustainability perspectives. Sustainable development is defined as “the simultaneous pursuit of economic prosperity, environmental quality, and social equity” (Elkington, 2013). Sustainable manufacturing thus employs processes that are non-polluting, conserve energy and natural resources, and are economically sound and safe for employees, communities, and consumers alike (Lozano, 2008).

2.1 Distinctive features of AM and their effects on sustainability

AM technologies enable manufacturers and product designers with some exclusive means of fabrication to address all the sustainability aspects. These exclusive strengths arose from the nature of AM including its layer-by-layer method of fabrication (leading to the complexity-for-free), tool-less manufacturing, and less-resource intensive.

AM facilitates the production of almost any geometrical complex design for which using conventional machining or casting is not possible or cost-effective. This advantage, known as *complexity-for-free*, implies that the production cost does not rely on the complexity of the design. This is due to the layer-by-layer nature of fabrication. Design freedom assists design optimization and introducing lattice structure leading to more light-weighted parts. Tang *et al.* (2016) empirically demonstrated that AM could significantly reduce energy consumption and emissions thanks to the design optimization that mainly owes to the lightweight design. Complexity-for-free offered by AM lets designers to integrate the components of a product. Designers can reduce the number of components through integrating more functionalities into a part so that it does not require further assembly (Yang and Zhao, 2015). Therefore, replacing one integrated assembly with several assembled components eliminates cost, time and quality problems of assembly operations (Ford and Despeisse, 2016). Furthermore, this feature of AM has several implications for the society, particularly on the quality of products. Design freedom promotes creativity and innovations yielding novel products with higher quality levels. The higher quality level is achievable through increased functionality, more durability, and ease of manufacturing and maintenance (Despeisse and Ford, 2015).

AM enables direct production from 3D CAD models, known as *direct digital manufacturing*. It does not entail tools and molds, thus there are almost no changeover time and costs, leading to a full flexible production system. The *tool-less* nature of AM exclusively empowers manufacturers to produce fully customized products in a sustainable manner. Although product customization is not exclusive, AM typically performs customization process without time and cost penalties. AM makes the concept of *economy-of-one* possible. Economy-of-one implies that there is the possibility of producing a single part in a cost-effective manner and in many cases at an even cheaper cost than conventional manufacturing. *Tool-less* fabrication is also beneficial for on-demand production that can eliminate the need for batch production and warehousing the finished products, leading to minimum inventory costs.

AM generally requires fewer number of resources (like material, energy, workforce, time, space, etc.) for production. This resource efficiency brings several benefits for economic, environmental and social sustainability. As stated in Holmström *et al.* (2017), thanks to AM, greener supply chains can be realized based on less intensive physical flows of products and subassemblies worldwide. AM offers maximum usage of materials because of the ability to reuse raw material (i.e. powder, resin), which has not been used during the operation (Ford and Despeisse (2016) estimated at 95-98% recyclability for metal powders).

Several researchers have studied the environmental sustainability of AM. Some compared the energy consumption of different AM technologies (e.g., Mognol *et al.,* 2006) and between AM and conventional manufacturing (e.g., Yoon *et al.,* 2014). Other researchers proposed design optimization methods to reduce energy consumption (e.g., Tang *et al.,* 2016), presented process parameter selection to optimize processing time and corresponding energy consumption (Yang *et al.,* 2017) and assessment of other environmental impacts (Yang and Li, 2018). Specific energy consumption (SEC) of AM processes is higher than that of conventional processes (Yoon *et al.,* 2014). In contrast, earlier studies demonstrated the energy-related efficiency of AM for small lots (Yoon *et al.,* 2014), for optimized designs (Baumers *et al.,* 2013), and for specific additive processes like Binder Jetting process (Tang *et al.,* 2016). In addition, considering the restructured value chain, the whole supply chain would be affected in terms of environmental sustainability. AM can improve the environmental performance of a firm through both operations to be done outside the manufacturing system (i.e. reducing or eliminating transportation through distributed manufacturing) and those operations inside the manufacturing system through less material usage and waste, design optimization, and optimum process parameter selection (Faludi *et al.,* 2015). Hence, it is clear that general conclusion for the energy consumption and environmental impacts of AM is not feasible and it is highly case-specific.

Table 1 Distinctive features of AM and their sustainability effects

FEATURES	DEFINITION	SUSTAINABILITY EFFECTS
COMPLEXITY-FOR-FREE	The geometrical and shape complexity of the product almost doesn't matter for layer by layer processes	• *Economic*: (1) Production costs do not rely on the complexity of the design (2) Boosted creativity and innovation through free-form fabrication and cost-effective iterations (3) Light-weighted components through manufacturing of lattice structure (4) Integrated and consolidated part through adding functionality of the components (5) Simplified assembly through design consolidation • *Social*: Co-design, democratized and consumer-centric manufacturing due to ease of design modifications
TOOL-LESS		• *Economic*:

	It does not require any tool, molds, etc.	(1) Economy of One rather than Economies-of-Scale due to minimum fixed-cost (2) Mass customization due to cost-effective production of single part or small lot (3) Real on-demand production due to economic production of small lot (4) Less inventory costs due to possible on-demand production (5) Flexible manufacturing due to diminished changeover time and cost (6) Gaining competitiveness due to reduced time-to-market
LESS RESOURCE-INTENSIVE	Less resources such as material, human, time, space are required for production	• *Economic*: Savings in delivery times and transportation costs due to possible distributed manufacturing • *Environmental*: (1) Increased material recycling rate (2) Lean production due to reduced waste generation (3) Green production due to less energy consumption and emissions (4) Green production due to less required resources such as space, time, workforce, etc. (5) Green production due to less material usage and material input • *Social*: Distributed (i.e. decentralized) manufacturing due to less required space and resources

Moreover, less-resource intensive feature of AM has social implications. The simple process of AM and less resource requirements enable developing economies to bridge the gap to high-tech manufacturing methods and to join this new emerging market along with advanced countries (Khorram Niaki and Nonino, 2018). AM may present health benefits for workforce as it allows operators to avoid a long-term presence in harsh and potentially hazardous working environments (Huang *et al.,* 2013). However, such impacts may exist during the processing and disposing of materials used in AM processes (Ford and Despeisse, 2016). Tang *et al.* (2016) argued that an additive process, called Binder Jetting is worse for human health than subtractive process. Less resource requirements together with ease of design modifications allow co-creation and consumer involvement in design and production of goods.

Aforementioned overviews classified the exclusive features of AM and their effects on economic, environmental, and social sustainability. Table 1 reports a summary of these distinctive features and their effects.

2.2 Current barriers to the AM diffusion

Several researchers investigated the technology diffusion challenges, attempting to find its barriers. There are still several technical limitations to the widespread diffusion of the technology (Durach *et al.,* 2017). R&D efforts focused on developing the wide range of raw material (Dwivedi *et al.,* 2017), increasing the speed of printing, enabling the production of large size products (Goodridge *et al.,* 2012), improving the quality of products (Thomas-Seale *et al.,* 2018), and in general boosting the efficiency and effectiveness of the technology to be faster, cheaper, and more reliable.

Besides these technical limitations, there are also some barriers to the adoption of the technology at the policy level (Khorram Niaki and Nonino, 2018). These drawbacks include the lack of standardization and legislation, the shortage of educated and skilled labor, concerns for intellectual property and protection (Baumers *et al.,* 2016), and the lack of information on suitability and availability of AM for production (Ford and Despeisse, 2016). Table 2 details and classifies the important barriers to the widespread adoption of AM technologies.

Table 2 Barriers to the widespread diffusion of AM technology

ITEMS GROUP		**BARRIERS**	**REFERENCES**
TECHNICAL	Machinery	• High cost of acquisition • Limit on size or build-chamber • Cost and speed of production • Uneven distribution of current AM services	Ruffo and Hague, (2007); Goodridge *et al.,* (2012); Ford and Despeisse, (2016)
	Material	• Limit on the range of materials • High cost of material • Difficulties of developing a new alloy • Mechanical properties of the materials • Limit on the material and part recyclability	Ford and Despeisse, (2016); Dwivedi *et al.,* (2017);
	Design	• Adapt the designers to new thinking • Lack of professional and integrated software for AM • Documents and design guidelines • Limited designs for home-use & beginners	Thomas-Seale *et al.,* (2018); Khorram Niaki and Nonino, (2018); Khorram Niaki and Nonino, (2017b)
	Process	• Problems with process repeatability • In-process monitoring and inspection • Automation of AM systems • Uncertain performance of products: stability, durability and reliability • Quality, accuracy and aesthetics of finished products • Cost efficiency of larger production volumes	Dwivedi *et al.,* (2017); Durach *et al.,* (2017); Ruffo and Hague, (2007); Baumers *et al.,* (2016); Khorram Niaki and Nonino, (2018); Bourell *et al.*, (2009); Thomas-Seale *et al.,* (2018); Ford and Despeisse, (2016)

		• Problems with post-processing	
POLICY	Standards	Relating to: • Equipment • Materials • Processes • Modelling • Test & quality inspections	Monzón *et al.,* (2015); Khorram Niaki and Nonino, (2018); Ford and Despeisse, (2016)
	Regulations	• Intellectual property; regarding copyright • Regulations relating to materials (e.g., biocompatibility)	Rogers *et al.*, (2016); Kietzmann *et al.,* (2015)
	Education	• Unavailability of qualified employees • Lack of information on technology affordability • Educating designers and engineers about the technology • Educating public communities and individual entrepreneurships about potential uses and benefits of AM	Dwivedi *et al.,* (2017); Baumers *et al.,* (2016); Ford and Despeisse, (2016)
	Behaviors	• Resistance to change/high-tech • Consumer awareness and acceptance • Lack of government/leadership support	Dwivedi *et al.,* (2017); Mellor *et al.,* (2014)

2.3 Determinants of AM adoptions

The literature on the management of AM has moved from its infancy and provides useful information for technology adopters (Khorram Niaki and Nonino, 2017a).

Oettmeier and Hofmann (2017) carried out a survey of 195 firms to identify multi-faceted factors that determine the decision to adopt AM. The results indicated that the demand-side benefits (i.e. production closer to the customer, customization and faster reaction to customer needs) and technology compatibility are the main determinants of AM adoption. As regards the relative advantages of AM, they asked respondents for the following impacts: cost reduction; improved material usage; freedom of design; ability to build lightweight products; ability to optimize products function and integrate more functionality into an object. Moreover, Schniederjans (2017) considered speed, quality, productivity, and employees’ effectiveness as the relative advantages of AM that might impact on the decision to adopt. These are interdisciplinary researches examining behavioral, engineering and managerial determinants through theoretical frameworks that might not cover the entire specific factors relating to AM. Since the existing theories are not linked with the adoption of advanced manufacturing technologies. Therefore, an exploratory research lacks in the literature to explain the decision to adopt AM. Moreover, the current literature does not consider the sustainability concerns. As stated before, Gebler *et al.* (2014) demonstrated that AM technologies would have huge potential sustainability implications on a product's lifecycle in terms of cost, energy and CO2 emissions. Thus, it is necessary to examine to what extent practitioners have realized these potentials and how they will consider these benefits in the decision to adopt AM.

In addition, different application sectors may have different expectations from a manufacturing technology, considering their manufacturing objectives. For instance, AM offers significant potentials for the aerospace industry, which needs parts with complex geometries, lower weights, and higher strength. The buy-to-fly rate in this industry typically reaches 15–20 (i.e., 15–20 kg are required to produce 1 kg of finished product), while AM could reduce this rate to nearly 1 (Cozmei and Caloian, 2012). Moreover, the supply chain of some aerospace spare parts is very slow and unpredictable. Therefore, many aerospace companies implemented AM technologies for these types of parts, which are high-cost and long-lead components. Automotive industries also employed AM technologies for a decade in prototyping, tooling and the production of special components. As stated in Khorram Niaki and Nonino (2017b), using AM could remove design constraints currently imposed on the automotive designer by tooling limitations. Medical sector is also one of the leading AM adopters because they usually need to produce parts with unique shape and higher functionality at a reasonable time (Khorram Niaki and Nonino, 2018). According to Bogue (2013), the ability to produce customized implants eliminates the need for time-consuming adjustments during surgery and reduces operating costs as well as the risk of medical complications. Consequently, these industrial examples clarify that the priorities and objectives of different industries in the adoption of AM might be different.

Thus, the paper contributes to expanding the literature by firstly, exploring the determinants of AM adoption, secondly, clarifying the role of sustainability benefits in the decision to adopt AM, and thirdly, identifying the priorities of AM adoption in different application sectors through a broad and multistage survey.

3. METHODOLOGY

This research explores the determinants of AM adoption with a particular attention on its sustainability perspectives and its importance in different application sectors. Thus, to answer our research questions, it was desirable to collect empirical data in multiple rounds survey as suggested by Delbecq and Van de Ven (1971). The method is employed in several similar researches in the field (e.g. Wieland *et al.,* 2016; Durach *et al.,* 2017). It is similar to the Delphi technique (Rowe and Wright, 2001), providing full anonymity to a panel of heterogeneous experts while allowing for a moderated exchange of ideas. Hence, we developed a two-round survey, including open- and close-ended questions in order to reach both qualitative information and quantitative rates.

The questionnaire in the first round included an open question asking "What are your main reasons for using AM (3D Printing) technologies?" (*See* Appendix 1. for details). This round is a part of a broader survey, analyzing the impact of AM on operations and business strategies and key driving factors of its performance. We designed the composition of the panel to be heterogeneous to foster creativity and to incorporate viewpoints from a variety of industries, operations, and organizations (Okoli and Pawlowski, 2004). Respondents could insert his/her three main reasons in the box. The unstructured first round of the survey gathered as many qualitative insights as possible. We sent the questionnaire to 807 companies (AM adopters) around the world. In total, excluding those, which were incomplete, 88 companies from 22 countries participated in this survey (about 11% of the total).

In the second round, the structured closed-ended questions (i.e. reasons) were subjected to measuring by experts. Purposive sampling strategy was employed, with a minimum quota of 2 firms required to represent the main AM application sectors. This strategy ensured a minimum number of cases in each category, yielding rich, generalizable, and believable information (Curtis *et al.*, 2000). We identified potential experts from the set whom we believed had expertise on AM technologies. We considered some factors for selecting experts among the set such as their experience in using the technology, being familiar with the technology and its features, and the position of the experts on the company. Since, top-managers are the most influential in the decision to adopt, technicians and other operational employees were excluded. Some of this information was available from the first round. For the others, we had an initial contact with 20 individuals to assess whether or not their qualifications were sufficient to consider them as the experts in our panel. Table 3 lists the important factors for selecting the experts' panel.

Table 3 Factors for selecting the experts' panel for the second round of the survey

Inclusion Criteria	**Exclusion Criteria**

Companies belonging to different countries	Companies do not involve in design or manufacturing
Companies belonging to main industrial sectors	Employees do not contribute to the decision of technology acquisition
The experience of the company in using the technology	Incomplete questionnaire
Gave consent to undertake study, i.e. “willingness to participate”	Technicians or operators of the technology

Finally, the selected reasons were sent to 15 experts asking them the priority of the reasons for using AM technologies (*See* Appendix 3. for detail). In total, considering those, which were completed, we obtained 12 responses from the experts participated in this stage. As the aim of the study, these respondents are experts in different AM application sectors including academia, automotive, aerospace, medical, and online 3D printing platforms (O3DP).

Regarding the criteria, we selected 10 factors among the 25 based on the frequency of received replies in the first round (*See* figure 2 for details). In addition, we consulted with some specialists from academia to verify our selected items and our survey design.

3.1 Weighting method

We employed a recently developed Multi-criteria decision-making (MCDM) approach, called Best-Worst Method (BWM) to rank the items (i.e. weighting the reasons). This method is argued to perform significantly better than other MCDM methods (e.g., analytic hierarchy process (AHP)) in terms of consistency ratio, the minimum violation, total deviation, and conformity (Rezaei, 2015). According to BWM prescriptions, the decision maker first selects the best (i.e. the most important reason) and the worst (i.e. the least important reason) criterion. Thus, we first asked our respondents to select the most/least important reason from the list. Then, the method suggests doing pairwise comparisons between the best/worst criterion and the other ones. Hence, we then asked our respondents to use a number between 1 and 9 to show the preference of the most important reason over the other reasons, and the preference of each reason over the least important reason (*See* Appendix 3. for detail). As suggested by Rezaei (2016), a linear problem (*see* equation 1; where ξ is consistency ratio; W_B: weight of the best factor; W_j: weight of factor j; W_W: weight of the worst factor; a_{Bj}: best-to-other vector; and a_{jW}: other-to-worst vector) is then formulated and solved in order to determine the optimum weight of each reason.

$$
\begin{gathered}
(1)\ \text{Minimize } \xi \\
s.t. \\
\left|W_B - W_j.a_{Bj}\right| \le \xi \text{ , } for\ all\ j \\
\left|W_j - W_W.a_{jW}\right| \le \xi \text{ , } for\ all\ j \\
\sum_j W_j = 1 \\
W_j \ge 0, for\ all\ j
\end{gathered}
$$

3.2 Sample descriptions

As mentioned before, 88 AM adopters were participated in the first round of the survey. Appendix 2 reports the generic demographic of the respondents, such as the development level of the country, number of employees and revenue and the position of the respondent. These companies were founded in major developed countries (72.7%), developed countries (20.5%) and developing countries (6.8%). The percentage can be representative of the population of AM adopters around the world, in which a few adopters belong to developing countries. This can be due to the developing phase or immaturity of the technology; however, Chen *et al.* (2015) argued that AM may bridge technological, educational and cultural gaps between developing and developed countries. The companies belong to different countries, of which USA (31%), Germany (12%), Italy (9%), France (9%) and UK (8%) constitute the most percentage of the sample.

Moreover, according to the classification suggested by European Commission and based on the revenue and number of employees, the sample includes small and medium enterprises (SMEs) (67%) and large companies (33%). The survey sample includes a variety of AM application sectors and industries such as automotive, aerospace, defense, electronics, medical, dental, education, architecture, art, jewelry, education and research institution, sporting goods, and food industries. A number of global and well-known companies participated in this survey such as General Electric, Renault, Renishaw, General Motors, Airbus, Ford Motor Company, Lamborghini, Bell & Howell, Ducati Motor Holding, Valeo, and Festo.

Appendix 1 also indicates the representativeness of the sample in terms of the main objective of using AM, the main used raw material, the production volume and the employed additive systems. The sample includes companies, which mainly implemented AM for prototyping (47.7%), manufacturing (43.2%), and for tooling purposes (9.1%). In addition, in terms of raw material, the sample includes companies that mainly use plastic (48.9%), metal (36.4%), ceramic (4.9 %) and other types of material (10.2%) such as composite nylon carbon fiber and new metal matrix composites. Additionally, 93.2 percent of the companies employed AM for low to medium production volumes and only 6.8 percent for large production volume. These companies use different types of AM technologies for their different requirements, 46 of those use Fused Deposition Modeling (FDM); 42 companies use Direct Metal Laser Sintering (DMLS); 40 companies use Selective Laser Sintering (SLS); 33 companies use Stereolithography (SLA); 16 companies use Electron Beam Melting (EBM); 7 companies use Laminated Object Manufacturing (LOM); and 14 companies use other additive systems that are not listed in the table such as DLP or PolyJet.

The participants of the second round of the survey were experts from different application sectors such as academia (25%), automotive (17%), aerospace (17%), medical (16%) and online 3D printing platforms (25%). These are the leading application sectors of AM technologies. The respondents in this stage were also appropriate for taking part in our analysis because they were all top-level executives and, on average, had more than 10 years of experience in the field of AM.

4. FINDINGS

As pointed out above, we first asked our respondents to determine their main reasons for using AM technologies. Each participant could answer three main reasons, providing preliminary qualitative data on AM technology adoption. Figure 2 shows the results of this open-ended question. It depicts the reasons considering the frequencies of respondents stating that reason. According to our research questions the following discussions respectively clarify the role of sustainability benefits on the decision to adopt AM, distinctive characteristics of AM and their effects on its adoption, and finally the ranking of main determinants and their importance in different AM application sectors.

4.1 The role of sustainability in AM adoption

As the figure shows, there are some factors relating to the economic, environmental and social sustainability. The results show that economic sustainability is one of the key determinants of AM adoption, since the two highly scored reasons are the ability of the technology for cost and time saving. Although previous researchers (e.g. Durach et al., 2017) argued that the speed of production and cost per unit of AM is still not competitive with conventional manufacturing, our observations reveal that a large number of the companies are motivated to adopt AM for time (23%) and cost saving purposes (24%). Argumentations provided in the literature implies the drawbacks of AM to serve mass production. However, a large number of our samples utilized AM for prototypes, test parts and concept models, for which using conventional methods are too time consuming and so costly. Moreover, companies benefited of tool-less nature of AM to rapidly and cost-effectively produce innovative designs, customized products and to run single production or a very small lot. In addition, versatile AM machines allow minimum changeover time and cost for even end-use products.

Unlike the economic motives, environmental and social dimensions of the sustainability are perceived to have lower effects in the decision to adopt. A few number of the companies in the sample (5 out of 88) pointed out the environmental reasons for AM adoption. Regarding the social sustainability, only one company among the sample considered the health benefits for AM adoption. Thus, our observations demonstrate that the environmental and social benefits do not constitute the key preferential factors of AM because very few companies are motivated by these factors.

On the other hand, there are some other factors in our observations that may have indirect impacts on environmental sustainability and can lead to a non-polluting value chain that conserves energy and natural resources. The prospect of AM for a localized supply chain may substantially reduce the needs for transportation of both raw materials and finished products. Localized supply chain allows a manufacturer to produce closer to the location of final consumers instead of centralized manufacturing (Ford and Despeisse, 2016). Although this concept has primary cost benefits, it has a supportive impact on environment since it can significantly decrease the transportation of goods. Moreover, the possibility of light-weighting can lead to conserve energy and raw materials. AM supports manufacturers to fabricate lattice structures and increase the strength-to-weight ratio of the parts. This capability has definitely cost benefits while it supports conserving resources and energy consumption in the whole product's lifecycle. It is particularly significant for aerospace industries, where additional 100 kg of the weight can increase the expenses of an airline by more than \$2.5 million in fuel consumption throughout the aircraft's lifecycle (Hopkinson *et al.,* 2006).

While, in our survey, we found that a few of the companies have paid significant attention to these potentials. Among the 88 research sample, only 10 companies utilized AM for lightweight parts, 5 for localized supply chain, and one for integrated components. Earlier studies argued that sustainability benefits would be realized when the full potential of AM would be exploited (e.g., Faludi *et al.,* 2015). Thus, companies will not benefit of ordinary rules (i.e., conventional product design and logistics) they used to employ for conventional manufacturing (Yang and Zhao, 2015). Instead, several researchers proposed specific guidelines for design with AM that may lead to both economic and environmental benefits.

Aforementioned discussions clarified that environmental and social benefits cannot solely motivate companies to adopt AM and are not part of its main drivers. However, we observed some reasons that incorporate beneficial side-effects for environment. Generally, environmental and economic sustainability are intertwined, even though in the case of AM economic side has been strongly realized in practice. Hence, environmental benefits of AM are perceived to have lower impact in the decision to adopt and this perception can be due to several possible reasons. First, despite the extremely optimistic views of academic researches, practitioners had not realized the considerable environmental benefits on-stream. Second, it can be due to either the lack of awareness of practitioners about the sustainability benefits of AM or the lack of attention to sustainability while choosing a manufacturing technology.

Studies have also shown the promising future of the technology (e.g., Gebler *et al.,* 2014) when the current technical drawbacks (e.g. speed and cost of production) will be resolved. Holmström et al. (2017) indicated that the production time required for a specific part had reduced about 450 percent from 2004 to 2014 thank to the technical progression of AM. Hence, it is reasonable to estimate the same trend in the future and to expect considerable economic and environmental benefits. Moreover, as highlighted in Section 2.1 the energy-related efficiency of AM is highly industry/case-specific. Our results also confirm this conclusion because 5 out of 88 respondents stated the green concerns as the reason to adopt AM.

4.2 Distinctive characteristics of AM and their effects on its adoption

Considering the distinctive characteristics of AM and their effects (synthesized in Table 1) and scores in the first round of the survey, tool-less capability, complexity-for-free and less-resource intensive features of AM had respectively higher degree of importance on the decision of AM adoption.

The tool-less capability, as the most important feature, caused the adoption of AM in 33 percent of the companies for rapid prototyping, 17 percent for cost-effective customization and 8 percent for low-volume production. Increased production flexibility, potentials for localized and on-demand supply chain are the other factors arising from this characteristic that attracted respectively 9, 6, and 4 percent of manufacturers to adopt AM technologies.

Complexity-for-free is the second effective characteristic for AM adoption. There are some factors in our observations affected by this feature. About 42 percent of companies in our sample are motivated to adopt AM to accelerate creativity and innovation processes, 25 percent to produce complex design, 11 percent to produce lightweight parts, 10 percent to improve part's functionality and less than one percent to integrate the components of a product.

Other reasons to adopt AM derive from its less-resource intensive capability. Approximately 6 percent of the companies adopted AM because it can lead to a greener production, 2 percent for less-required labor, 3 percent because it requires lower investment and less than one percent to avoid occupational health hazards. Therefore, these factors could slightly affect the decision to adopt in comparison with the two other distinctive characteristics of AM (i.e. complexity-for-free and tool-less fabrication). Thus, our findings show the least importance of these benefits for decision makers to adopt the technology.

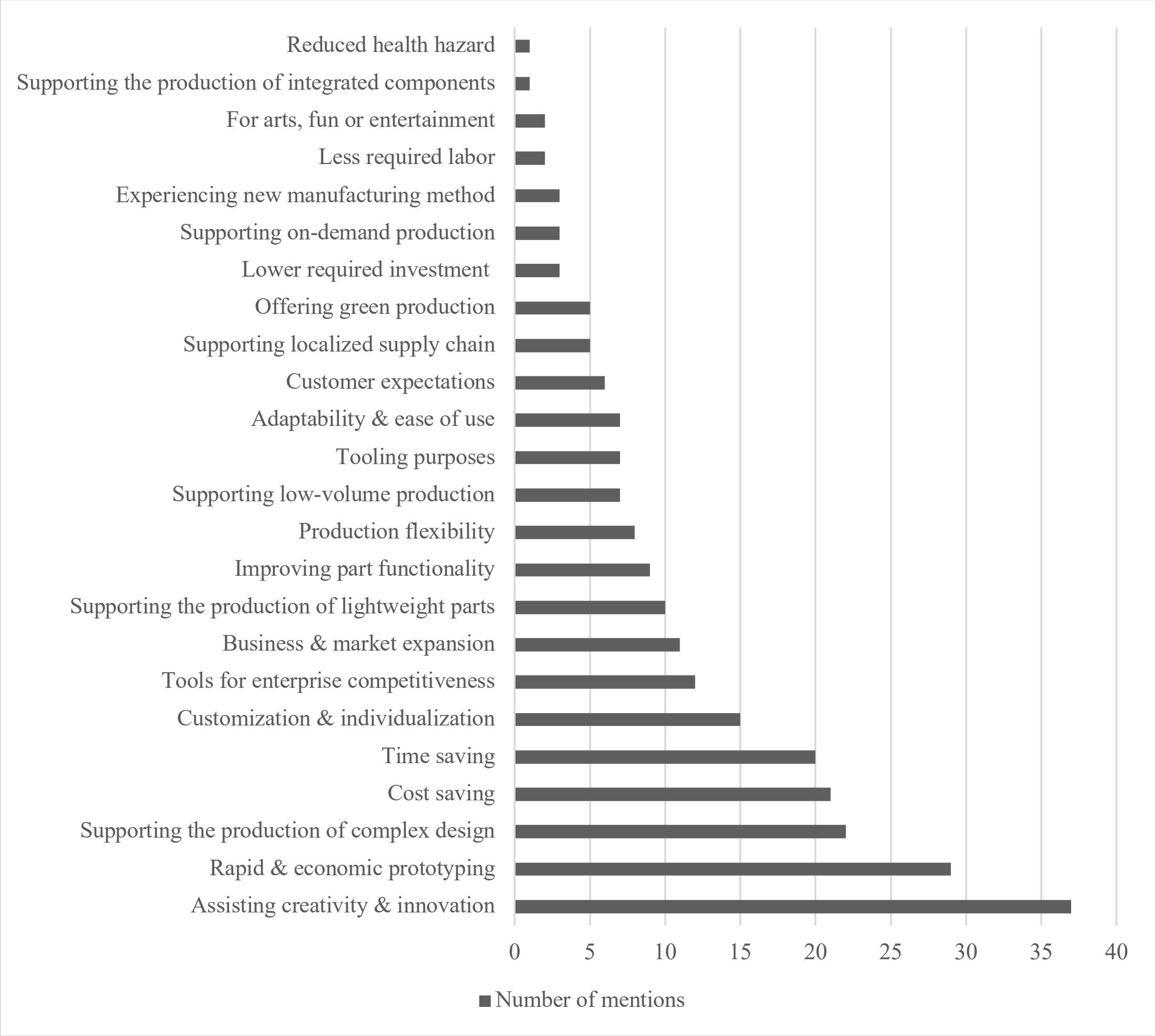

Fig. 2. Reasons for adopting AM technologies (Data gathered from the survey of 88 AM adopters)

4.3 Ranking of determinants and their importance in different application sectors

The outcomes of the first round of the survey are employed to choose the important criteria for the second round, asking from the expert panel to order the factors. The first six factors (highly scored) have been directly used in the second round. We then consulted academic specialists to select among the other factors considering the likely overlapping between the items. Moreover, we attempted to involve more dimensions such as organization and operations into the set of factors as suggested in the earlier literature (e.g. Oettmeier and Hofmann, 2017). Finally, we selected ten key items that are likely to be more influential in the decision to adopt AM. These factors include creativity and innovation, rapid & economic prototyping, production of complex design, cost saving, time saving, customization capability, business & market expansion, low-volume production, customer expectations, and technology adaptability (respectively termed as R1 to R10 in Table 4).

Table 4 reports the aggregated weight of the selected determinants of AM adoption, calculated by BWM. The consistency ratio of required pairwise comparisons is less than the threshold of 0.1, indicating the suitability of the estimated weights (Saaty, 1989). The analysis is based upon the opinion of various application sectors including experts from academia, automotive, aerospace, medical, and online 3D printing platforms. The aggregate analysis reveals that the most important determinant is the ability to produce complex part, followed by customization capability and creativity and innovation. Technology adaptability of the technology is perceived to be the least important one. As discussed before, AM allows designers to bypass the common design constraints imposed by conventional manufacturing and therefore almost any intricate design can be directly translated into the physical object. This capability offers many other benefits to manufacturers such as producing light-weighted parts, manufacturing consolidated product that needs less assembly operations, and promoting creativity and thus customer’s satisfaction. The opinions held by these AM application sectors are inconsistent. Among which, online 3D printing (O3DP) platforms have extremely different opinions on the determinants of the AM adoption.

Table 4 Ranking of the determinants of AM adoption

Determinants of AM adoption		Academia		Automotive		Aerospace		Medical		Online 3DP Platforms (O3DP)		Synthesized	
		Weight	Rank	Weight	Rank	Weight	Rank	Weight	Rank	Weight	Rank	Weight	Rank
R1	Creativity and innovation	0.163	1	0.067	7	0.110	3	0.076	7	0.039	10	0.099	3
R2	Rapid & economic prototyping	0.078	6	0.093	6	0.101	4	0.086	5	0.077	4	0.086	5
R3	Production of complex design	0.157	2	0.178	1	0.307	1	0.180	2	0.077	5	0.184	1
R4	Cost saving	0.047	9	0.097	5	0.157	2	0.073	8	0.093	3	0.078	6
R5	Time saving	0.070	7	0.153	3	0.055	7	0.123	3	0.136	1	0.076	7
R6	Customization capability	0.104	3	0.157	2	0.062	6	0.187	1	0.102	2	0.103	2
R7	Business & market expansion	0.040	10	0.047	8	0.050	8	0.081	6	0.066	8	0.065	8
R8	Low-volume production	0.104	4	0.132	4	0.085	5	0.062	9	0.075	7	0.089	4
R9	Customer expectations	0.082	5	0.033	10	0.047	9	0.111	4	0.077	6	0.058	9
R10	Technology adaptability	0.065	8	0.044	9	0.028	10	0.024	10	0.058	9	0.035	10

Application Sectors: Academia, Automotive, Aerospace, Medical, Online 3DP Platforms (O3DP)

As regards academic experts, they believed that the role of AM in accelerating creativity and innovation (R1: 0.163) is the most important determinant of AM adoption, where the other sectors hold opposing viewpoints for this element. Likewise the other sectors, they also verified the importance of complexity-for-free criterion (R3: 0.157). The third most important reason is the capability of AM for product customization (R6: 0.104), which is among the top three determinants of the other application sectors.

According to the opinion of experts from the automotive industry, the customization capability (R6: 0.157) and potentials for time saving (R5: 0.153) has the most importance after the complexity-for-free criterion (R3: 0.178). Time saving factor has the same priority rank for the medical sector, and even more for the online 3D printing platforms.

Regarding the aerospace industry, they considered the cost saving (R4: 0.157) element as the most important factor after complexity-for-free criterion (R3: 0.307). The cost saving element does not have this priority rank on the other sectors except the 3D printing platforms. Moreover, unlike the automotive industry, time saving (R5: 0.055) and customization capability (R6: 0.062) do not have so pivotal role in aerospace industries.

The results exhibit that the medical industry considered customization capability (R6: 0.187) as the leading factor. Complexity-for-free (R3: 0.180) and time saving (R5: 0.123) are the second and third priorities according to their opinions. The criterion of customer expectation (R9: 0.111) is the fourth priority, holding the highest priority among the other sectors.

As regards the online 3D printing platforms, the respondents believed that the top three determinants are time saving, customization capability, and cost saving potentials (R5: 0.136; R6: 0.102; R4: 0.093), whereas accelerating creativity and innovation (R1: 0.039), and adaptability (R10: 0.058) are the least important reason for AM diffusion in this sector.

Finally, the aggregate analysis of the data demonstrate that complexity-for-free, customization capability, and accelerating creativity and innovation are given respectively first, second and third priorities (R3: 0.184; R6: 0.103; R1: 0.099). In contrast, three least important factors to adopt AM technology include adaptability, customer expectations, and business and market expansion (R10: 0.035; R9: 0.058; R7: 0.065). Generally, these criteria are considered as the determinants of the AM technology adoption; however, these may have different priorities on different application sectors. Figure 3 illustrates the differences of the factors to adopt AM technology in various application sectors.

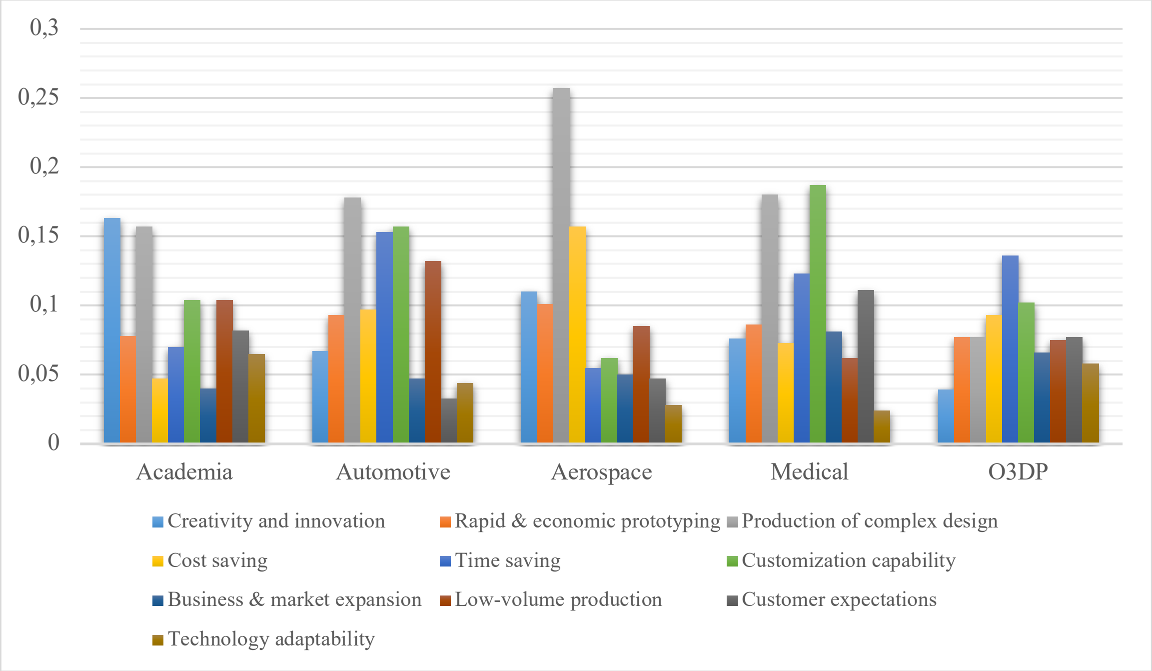

Fig. 3. Priorities of AM adoption in different application sectors

5. CONCLUSIONS AND FUTURE RESEARCH

The aim of the research was to empirically identify and prioritize the determinants of AM adoption in different application sectors. In addition, the special emphasis was to determine the role of sustainability benefits in adoption. This empirical study involved a two-round survey research.

In the first round, we asked for three main adoption reasons from AM users using an open-ended question. The qualitative data and analysis of the first round show that the economic sustainability is the primary reason for AM adoption, while social and environmental sustainability benefits are the least important drivers of its adoption. The findings relating to the social sustainability benefits were expected. Previous researchers indicated that AM is far from a massive impact on the society, since the technology is still growing and its social impact will be realized once the general public acquires a good understanding of AM (Huang *et al.,* 2015). Regarding the environmental sustainability benefits, the results are in contrast to the literature demonstrating the huge benefits of AM for being an environment-friendly production (e.g. Gebler *et al.,* 2014; Holmström *et al.*, 2017). Our observations indeed show that a few percent of our respondents adopted AM because of environmental benefits. In addition, considering the distinctive characteristics of AM, the tool-less nature of AM, complexity-for-free and less-resource intensive feature has respectively higher degree of importance on the decision to adopt.

In the second round, experts measured the qualitative refined data, obtained from the first round. The synthesized analysis shows that the ability of AM for manufacturing complex parts, facilitating customization and assisting creativity and innovation are the most important motives of AM adoption. Therefore, our findings suggest those industries and manufacturers with these priorities to implement AM, since their competitors with the same priorities are verifying its effectiveness.

Consistent with the recent literature, our findings confirm that two factors such as technology compatibility (Schniederjans, 2017) and the effect of external pressures (Yeh and Chen, 2018) are less important in the decision to adopt. Our study reveals the less importance of adaptability and customer expectations on AM adoption. Moreover, manufacturers do not consider business and market expansion as an important reason to acquire AM. Therefore, factors related to the production and supply chain management play the pivotal role in the decision to adopt AM and accordingly, on the preference of AM technology over conventional manufacturing methods. This finding is of utmost importance for future research trying to find the determinants of AM adoption through interdisciplinary theories (i.e. Technology Diffusion or Technology acceptance theories). Our study clarifies the order and the importance of AM relative advantages and suggests the importance of factors related to products and production to explain the adoption of AM technologies.

This study also distinguishes the importance of such factors in different application sectors. The respondents of the second round were experts from different AM application sectors including academia, aerospace, automotive, medical, and 3D printing platforms. In general, the results indicate that the sector’s priorities in using AM are inconsistent. Consequently, first, potential users or industries may benefit from this research by identifying capabilities of AM in different contexts. Industrial firms are stimulated to benchmark based upon their priorities before adopting new manufacturing technologies. Second, AM vendors may use the findings to get more insights from different industry’s motives to use AM. This can help them to learn their consumer’s behavior in purchasing and to improve their offerings and target customers more effectively. Regarding the two main application sectors including aerospace and automotive industries, the former considers cost-saving as the most important determinant of AM adoption, while in the latter time-saving is of the utmost importance. Time-saving is mostly obtainable in new product development processes, whereas cost-saving is rather achievable in manufacturing of end-usable products. Moreover, as stated before, AM is considered as an efficient method mostly for high-value parts and low-volume production due to its capability in reducing wastes. Thus, it matches the characteristics of the aerospace industry. In contrast, AM loses its efficiency in mass production; however, it maintains its capability to speed up the R&D operations.

The experts from medical sector stated that AM capabilities for customization and time-saving are the most important reasons to adopt. Usually, there is a limited time for the fabrication of medical components therefore the most suitable manufacturing method is the one that can rapidly produce parts, while maintaining the same quality level. Typically, medical products (e.g. hearing aids) or tools (surgical guides) need to be customized to the patient's size and shape that is too time-consuming and expensive using conventional methods (i.e. casting or handcrafting).

Online 3D printing Platforms selected another order for the importance of the criteria affecting the decision to adopt. Although they are already using AM, the results help to understand which kind of technology or AM machines are the order-winner in these marketplaces. The results show that time-saving is the most important criteria, followed by customization capability, and cost-saving. Therefore, they consider these factors in acquiring AM equipment, and thus AM vendors should consider these factors as the source of their competitive advantages.

The research took into account a limited number of industries. Thus, further research should cover more application sectors and should compare the results with non-adopter. We employed a survey research to understand to what extent sustainability benefits have been realized, while survey generally lacks a deep understanding of the phenomenon. Moreover, it is evident that the performance and accuracy of different AM technologies may vary. Thus, further research should use in-depth case studies of different industrial sectors and AM technologies in order to explore unidentified variables.

REFERENCES

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.

Baumers, M., Tuck, C., Wildman, R., Ashcroft, I., Rosamond, E. and Hague, R., 2013. Transparency built-in: Energy consumption and cost estimation for additive manufacturing. *Journal of Industrial Ecology*, *17*(3), pp. 418-431.

Berman, B., 2012. 3-D printing: The new industrial revolution. *Business horizons*, *55*(2), 155-162.

Bogers, M., Hadar, R., Bilberg, A., 2016. Additive manufacturing for consumer-centric business models: Implications for supply chains in consumer goods manufacturing. *Technological Forecasting and Social Change*, *102*, 225-239.

Bogue, R., 2013. 3D printing: the dawn of a new era in manufacturing? *Assembly Automation*, 33 (4), 307–311.

Bourell, D. L., Leu, M. C., Rosen, D. W., 2009. Roadmap for additive manufacturing: identifying the future of freeform processing. *The University of Texas at Austin, Austin, TX*, 11-15.

Chen, D., Heyer, S., Ibbotson, S., Salonitis, K., Steingrímsson, J.G. and Thiede, S., 2015. Direct digital manufacturing: definition, evolution, and sustainability implications. *Journal of Cleaner Production*, 107, pp. 615-625.

Cozmei, C. and Caloian, F., 2012. Additive manufacturing flickering at the beginning of existence. *Procedia Economics and Finance*, 3, 457-462.

Curtis, S., Gesler, W., Smith, G., Washburn, S., 2000. Approaches to sampling and case selection in qualitative research: examples in the geography of health. *Social science & medicine*, *50* (7-8), 1001-1014.

D'Aveni, R. 2015. The 3-D Printing Revolution. *Harvard Business Review,* 93(5), 40-48.

Delbecq, A. L., Van de Ven, A. H. 1971. A group process model for problem identification and program planning. *The Journal of Applied Behavioral Science*, *7*(4), 466-492.

Despeisse, M. and Ford, S., 2015, September. The role of additive manufacturing in improving resource efficiency and sustainability. In *IFIP International Conference on Advances in Production Management Systems* (pp. 129-136). Springer, Cham.

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.

Dwivedi, G., Srivastava, S. K., Srivastava, R. K., 2017. Analysis of barriers to implement additive manufacturing technology in the Indian automotive sector. *International Journal of Physical Distribution & Logistics Management*, *47*(10), 972-991.

Elkington, John. "Enter the triple bottom line." In *The triple bottom line*, pp. 23-38. Routledge, 2013.

Faludi, J., Bayley, C., Bhogal, S. and Iribarne, M., 2015. Comparing environmental impacts of additive manufacturing vs traditional machining via life-cycle assessment. *Rapid Prototyping Journal*, *21*(1), pp. 14-33.

Ford, S., Despeisse, M., 2016. Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. *Journal of Cleaner Production*, *137*, 1573-1587.

GE. 2015. *"GE Brilliant Factory"*. Retrieved from https://www.ge.com/stories/brilliantfactory

Gebler, M., Uiterkamp, A.J.S. and Visser, C., 2014. A global sustainability perspective on 3D printing technologies. *Energy Policy*, *74*, pp. 158-167.

Goodridge, R. D., Tuck, C. J., Hague, R. J. M., 2012. Laser sintering of polyamides and other polymers. *Progress in Materials Science*, *57*(2), 229-267.

Holmström, J., Liotta, G. and Chaudhuri, A., 2017. Sustainability outcomes through direct digital manufacturing-based operational practices: A design theory approach. *Journal of Cleaner Production*, *167*, pp. 951-961.

Huang, S.H., Liu, P., Mokasdar, A. and Hou, L., 2013. Additive manufacturing and its societal impact: a literature review. *The International Journal of Advanced Manufacturing Technology*, *67*(5-8), pp. 1191-1203.

Huang, Y., Leu, M.C., Mazumder, J. and Donmez, A., 2015. Additive manufacturing: current state, future potential, gaps and needs, and recommendations. *Journal of Manufacturing Science and Engineering*, *137*(1), p. 014001.

Jiang, R., Kleer, R. and Piller, F.T., 2017. Predicting the future of additive manufacturing: A Delphi study on economic and societal implications of 3D printing for 2030. *Technological Forecasting and Social Change*, *117*, pp. 84-97.

Khorram Niaki, M., Nonino, F. 2017a. Additive manufacturing management: A review and future research agenda. *International Journal of Production Research*, *55*(5), 1419-1439.

Khorram Niaki, M., Nonino, F. 2017b. Impact of additive manufacturing on business competitiveness: A multiple case study. *Journal of Manufacturing Technology Management*, *28*(1), 56-74.

Khorram Niaki, M., Nonino, F., 2018. *The Management of Additive Manufacturing: Enhancing business value*. Springer, Cham.

Kietzmann, J., Pitt, L., Berthon, P., 2015. Disruptions, decisions, and destinations: Enter the age of 3-D printing and additive manufacturing. *Business Horizons*, *58*(2), 209-215.

Lozano, R., 2008. Envisioning sustainability three-dimensionally. *Journal of cleaner production*, *16*(17), pp. 1838-1846.

Mellor, S., Hao, L., Zhang, D., 2014. Additive manufacturing: A framework for implementation. *International Journal of Production Economics*, *149*, 194-201.

Mognol, P., Lepicart, D. and Perry, N., 2006. Rapid prototyping: energy and environment in the spotlight. *Rapid prototyping journal*, *12*(1), pp. 26-34.

Monzón, M. D., Ortega, Z., Martínez, A., Ortega, F., 2015. Standardization in additive manufacturing: activities carried out by international organizations and projects. *The international journal of advanced manufacturing technology*, *76*(5-8), 1111-1121.

Oettmeier, K., Hofmann, E., 2017. Additive manufacturing technology adoption: an empirical analysis of general and supply chain-related determinants. *Journal of Business Economics*, *87*(1), 97-124.

Okoli, C., Pawlowski, S. D., 2004. The Delphi method as a research tool: an example, design considerations and applications. *Information & management*, *42*(1), 15-29.

Rao, R., 2016. *How GE is using 3D printing to unleash the biggest revolution in large scale manufacturing in over a century*. Retrieved August 4, 2016, from TechRepublic: http://www.techrepublic.com/article/how-ge-is-using-3d-printing-to-unleash-the-biggest-revolution-in-large-scale-manufacturing

Rayna, T., Striukova, L., Darlington, J., 2015. Co-creation and user innovation: The role of online 3D printing platforms. *Journal of Engineering and Technology Management*, *37*, 90-102.

Rezaei, J., 2015. Best-worst multi-criteria decision-making method. *Omega*, *53*, 49-57.

Rezaei, J., 2016. Best-worst multi-criteria decision-making method: Some properties and a linear model. *Omega*, *64*, 126-130.

Rogers, H., Baricz, N., Pawar, K. S., 2016. 3D printing services: classification, supply chain implications and research agenda. *International Journal of Physical Distribution & Logistics Management*, *46*(10), 886-907.

Rowe, G., & Wright, G., 2001. Expert opinions in forecasting: the role of the Delphi technique. *In Principles of forecasting* (pp. 125-144). Springer, Boston, MA.

Ruffo, M., Hague, R., 2007. Cost estimation for rapid manufacturing simultaneous production of mixed components using laser sintering. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *221*(11), 1585-1591.

Saaty, T. L., 1989. Decision making, scaling, and number crunching. *Decision Sciences*, *20*(2), 404-409.

Schniederjans, D. G., 2017. Adoption of 3D-printing technologies in manufacturing: A survey analysis. *International Journal of Production Economics*, *183*, 287-298.

Stratasys, 2015. *Stratasys Additive Manufacturing Chosen by Airbus to Produce 3D Printed Flight Parts for its A350 XWB Aircraft*. Retrieved January 14, 2016, from Stratasys Blog: http://blog.stratasys.com/2015/05/06/airbus-3d-printing/

Tang, Y., Mak, K. and Zhao, Y.F., 2016. A framework to reduce product environmental impact through design optimization for additive manufacturing. *Journal of Cleaner Production*, *137*, pp. 1560-1572.

Thomas-Seale, L. E. J., Kirkman-Brown, J. C., Attallah, M. M., Espino, D. M., Shepherd, D. E. T., 2018. The barriers to the progression of additive manufacture: Perspectives from UK industry. *International Journal of Production Economics*.

Ullah, A.S., Hashimoto, H., Kubo, A. and Tamaki, J.I., 2013. Sustainability analysis of rapid prototyping: material/resource and process perspectives. *International Journal of Sustainable Manufacturing*, *3*(1), pp. 20-36.

Weller, C., Kleer, R. and Piller, F.T., 2015. Economic implications of 3D printing: Market structure models in light of additive manufacturing revisited. *International Journal of Production Economics*, *164*, pp. 43-56.

Wieland, A., Handfield, R. B., Durach, C. F., 2016. Mapping the landscape of future research themes in supply chain management. *Journal of Business Logistics*, *37*(3), 205-212.

Yang, S. and Zhao, Y.F., 2015. Additive manufacturing-enabled design theory and methodology: a critical review. *The International Journal of Advanced Manufacturing Technology*, *80*(1-4), pp. 327-342.

Yang, Y. and Li, L., 2018. Total volatile organic compound emission evaluation and control for stereolithography additive manufacturing process. *Journal of Cleaner Production*, *170*, pp. 1268-1278.

Yang, Y., Li, L., Pan, Y. and Sun, Z., 2017. Energy consumption modeling of stereolithography-based additive manufacturing toward environmental sustainability. *Journal of Industrial Ecology*, *21*(S1), pp. S168-S178.

Yeh, C.C. and Chen, Y.F., 2018. Critical success factors for adoption of 3D printing. *Technological Forecasting and Social Change*, *132*, pp. 209-216.

Yoon, H.S., Lee, J.Y., Kim, H.S., Kim, M.S., Kim, E.S., Shin, Y.J., Chu, W.S. and Ahn, S.H., 2014. A comparison of energy consumption in bulk forming, subtractive, and additive processes: Review and case study. *International Journal of Precision Engineering and Manufacturing-Green Technology*, *1*(3), pp. 261-279.

Appendices

Appendix 1.

Survey items of the first round

Items		Questions
Main question	Reasons to adopt	What are your main reasons for using AM (3D Printing) technologies?
Firmographic	Country Development Level	In what country is your company currently headquartered?
	Number of employees	About how many employees work at your company? *≤ 50; ≤ 250; > 250*
	Approximate sales volume (€)	How much were your company's approximates sales in the last year? *≤ 2 Million; ≤ 10 Million; ≤ 50 Million; > 50 Million*
	Aim of use	Which of the following best describes your (or main) AM implementation objectives? *Rapid Prototyping; Rapid Manufacturing; Rapid Tooling*
	Types of material	Which type of material does your company use (or mainly use) in additive manufacturing? *Plastic; Metal; Ceramic; Other*
	Production volume	Which of the following best describes the size of your production lot? *Small; Medium; large*
	AM systems	Which type of technology your company currently uses? *FDM, DMLS, SLS, SLA, EBM, LOM, Other Systems*

Appendix 2.

Case summaries of the first round

Firmographic	Frequency	Percent
Country Development Level		
Major Developed Countries	64	72.7
Developed Countries	18	20.5
Developing Countries	6	6.8
Number of employees		
50 employees or less	50	56.8
51–250 employees	9	10.2
Over 250 employees	29	33.0
Approximate sales volume (€)		
Less than 2 million	43	48.9
2 million to 10	12	13.6
10 million to 50	10	11.4
Over 50 million	23	26.1
Positions of the respondents		
CEO-CTO- President-VP	38	43.2
Director	23	26.1
R&D-Design-Operation manager	17	19.3
Other	10	11.4
Aim of use		
Prototyping	42	47.7
Manufacturing	38	43.2
Tooling	8	9.1
Types of Material		
Plastic	43	48.9
Metal	32	36.4
Ceramic	4	4.5
Other Material	9	10.2
Production Volume		
Low	66	75.0
Medium	16	18.2
Large	6	6.8
Additive systems*		
FDM	46	
DMLS	42	
SLS	40	
SLA	33	
EBM	16	
LOM	7	
Other Systems	14	

* (Fused Deposition Modeling (FDM); Direct Metal Laser Sintering (DMLS); Selective Laser Sintering (SLS); Stereolithography (SLA); Electron Beam Melting (EBM); Laminated Object Manufacturing (LOM))

Appendix 3.

Survey items of the second round

1. *Please select the MOST IMPORTANT reason from the 10 reasons for adopting AM (first line), and insert it in the most left-hand side cell of the second row.* Now use a number between 1 and 9 to show the preference of the MOST IMPORTANT reason over the other criteria.

Table A

The MOST IMPORTANT Reason	Creativity & innovation	Rapid & economic prototyping	Production of complex design	Cost saving	Time saving	Customization & individualization	Business & market expansion	Low-volume production	Customer expectations	Adaptability or ease of use

(1= The MOST IMPORTANT reason is equally preferred with this criterion; 3= moderately preferred; 5= strongly preferred; 7= very strongly preferred; 9= extremely preferred)

2. *Please select the LEAST IMPORTANT reason from the 10 reasons for adopting AM (first column), and insert it in the top cell of the second column.* Now use a number between 1 and 9 to show the preference of the criteria over the LEAST IMPORTANT criterion.

Table B

The LEAST IMPORTANT Reason	
Creativity & innovation	
Rapid & economic prototyping	
Production of complex design	
Cost saving	
Time saving	
Customization & individualization	
Business & market expansion	
Low-volume production	
Customer expectations	
Adaptability or ease of use	

(1 = This criterion is equally preferred with the LEAST IMPORTANT reason; 3= moderately preferred; 5= strongly preferred; 7= very strongly preferred; 9= extremely preferred))