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State of the art of additive manufacturing: Review for tolerances, mechanical resistance and production costs

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Abstract: The new technology named additive manufacturing (AM) is gaining significance in the industrial sector due to its capacity to define new improvements in the design, production and logistical issues related to a specific product. This new area in industrial engineering is becoming operative but is still not easily applicable to all types of production systems. Many research and practical contributions have been developed in the last few years, but a unique answer for a possibility to be applied to the industrial sector has not yet been derived. This paper aims to analyse existing research literature on AM application in the industrial sector and tries to determine the open issues related to this theme. Here the themes on the mechanical and chemical characteristics of the materials produced with AM and the management theme are examined.

Subjects: Mechanical Engineering; Manufacturing Technology; Operations Management

Keywords: additive manufacturing; advanced production systems; operations; materials; tolerance limitation

1. Introduction

The industrial world is focusing on additive manufacturing (AM) as it appears to be a technology that could realize a new revolution for industrial manufacturing systems. AM was discussed and analysed in international literature on AM during the mid-1990s (Sachs et al., 1993) using a study by a research group of the Massachusetts Institute of Technology (MIT). They first attempted to state the problem of 3D manufacturing. The integration of 3D manufacturing with the traditional way to produce

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The authors of the paper entitled “State of the art of additive manufacturing: Review for tolerances, mechanical resistance and production costs” constitute a part of a greater research group focused on the themes of the operations design, management and optimization.

PUBLIC INTEREST STATEMENT

The paper entitled “State of the art of additive manufacturing: Review for tolerances, mechanical resistance and production costs” deals with the identification of the future research main stream in the field of the metal additive manufacturing (AM) in the industries. This is done analysing in detail the state of the art about the quality and capability that the AM technology can achieve nowadays and after analysing the theme of the operations management related to the introduction of this new technology in the industrial production context. This paper is one of the first products of a more general research about a new management and optimization model that deals with the integration of the AM in the traditional industrial context.

objects was also described. It is important to underline that AM in the years after its birth has been investigated as a new technology capable of realizing a product directly and autonomously. The first examples of the use of AM in the field of production were recognizable in the production of polymer material objects; this was mainly due to the machines' technology (Kim & Shahinpoor, 2002; Kruth, Leu, & Nakagawa, 1998; Levy, Schindel, & Kruth, 2003). In these years, i.e. from the mid-1990s to the beginning of the new century, considerable attention was paid to this new technology from the sector of biomanufacturing and concerning its possibility to create a completely new industrial sector that needs considerable applicability research (Feldman & Ronzio, 2001; Ferreira, Alves, & Bartolo, 2004; Lysaght & Hazlehurst, 2004; Sun, Starly, Nam, & Darling, 2005; Yan, Wu, Zhang, Xiong, & Lin, 2003).

Subsequently, some years later, 3D printing (known as AM) was introduced to the practitioners' world of metal products. Therefore, many of the theoretic hypotheses and problems were found to be real. The application of this technology in real cases or in technological laboratories led to an outbreak of not only a lot of opportunities but also criticalities in its application.

In recent years, AM has been employed in some first pilot production systems for the aerospace and aeronautic sector in application laboratories in collaboration with MIT (Duerden, 2011; LaMonica, 2013). Their productions focused on small volume products, as it was the first attempt of experiments in this field. From these applications, the industries, together with primary universities, are trying to understand the applicability of this new technology to substitute or at least integrate their traditional production systems with these new ones by recognizing an opportunity in AM to optimize their processes with particular focus on the designs, engineering, production and logistics.

It is difficult to find a systematic approach in the international literature for AM to encounter the challenges that the industry is currently prioritizing research on. In particular, the issues realized by industries are the themes related to the integration of this technology in normal production systems and the capacity to standardize, design and manage a production system that uses AM as its main production technology.

This paper aims to present a state of the art that can cover three relevant sectors of the industrial system management problem; two of these are referred to as the applicability hypothesis of this technology to the industrial world (analysing the mechanical characteristics of the materials processed and the tolerance of the processing achievable through AM). The last one is referred to as the management method for AM, in particular, the measurement of costs for the processes of AM production methods. Another information, such as the year of publication, is investigated to create a timeline of the papers. This was done to better understand the origins of the works on this issue.

2. Literature review method

Before we start with the literature review, it is important to work on the method used. It is possible to approach the problem by defining a method to analyse and select the papers to be analysed because the number of papers is quite large. The procedure followed included the following steps:

- Definition of keywords.
- Collection of papers from the best paper database, divided between materials and tolerances and operations applied in AM.
- Papers' characteristic analysis.
- Lack of literature identification.

From a wide range of effective materials that can be produced using AM, we concentrated on metallic and titanium alloys. These two materials are used in aerospace and mechanical machining products. In particular, the first sector seems to be one of the most promising industrial sectors because of several reasons such as the very-low ratio of *buy-to-fly*, the medium-high complexity of the parts mounted, is mounted on the aircraft parts and material purchasing costs.

The databases used to individuate the papers (almost 100) to be analysed are Scopus, Web of Science, Science Direct, Google Scholar, EBSCO and many others.

3. Literature review

3.1. Literature review on quality and capability of AM production

The research theme on metal materials used for AM is a deeply investigated topic (Frazier, 2014). In the international literature, there are many contributions in this sector, as mechanical property analysis and characterization are the two main issues investigated since a couple of decades. In this paper, we focused on these themes because hypotheses have been provided on the effective possibility to apply this technology, when compared with the traditional technologies, to a real industrial case. After this investigation, we focused on the geometrical complexity of the pieces to be realized as the main key factor of differentiation of the AM technology from the traditional machining tools.

The keywords used were as follows: (i) materials for additive manufacturing, (ii) production tolerances for additive manufacturing, (iii) metallic materials for additive manufacturing, (iv) non-metallic materials for additive manufacturing, (v) complexity for free and (vi) geometrical complexity in AM and similar or combinations of the previous words.

The published papers covered a time span from 1999 to the present. The research was mainly developed and conducted in Germany and USA; however, countries from all around the world have a good number of publications in this research area.

The main topics studied are titanium alloys and other metallic materials produced using the AM production technology.

In this paragraph, the production tolerance problem is first examined. This issue is very important to better understand if the products processed using AM technology need different cycles of processing as compared to pieces processed using subtractive technology. This section of the study aims to understand the level of tolerances achievable from this new technology and whether the use of AM needs a complex post-processing work to achieve the tolerances that are achievable with the traditional working technology.

In 2011, some authors investigated the effect of the part orientation on the production geometrical tolerances achievable from a rapid manufacturing process (Ratnadeep & Sam, 2011). They emphasized that geometrical tolerances were not deeply investigated until their study. However, other studies conducted before the study by Ratnadeep and Sam are also present. In particular, there are the studies by Arni and Gupta that analyse the planarity tolerance using AM technology (Arni & Gupta, 1999) and by Hanumaiah and Ravi for the planarity, linearity and circularity geometrical tolerances (Hanumaiah & Ravi, 2007). Moreover, it is possible to say that only one paper (Ollison & Berisso, 2010) provided the effects of a production parameter on the geometrical tolerance of circularity in AM (i.e. the error is minimized if the starting cut angle is equal to 0°). However, a more detailed study on the geometrical tolerances achievable through proper parameter setting is provided in a paper by Lynn-Charney and Rosen (2000), which investigated and proposed a decision support system to minimize the errors for positioning, planarity, parallelism, perpendicularity, concentricity and circularity.

In another paper (Boschetto & Bottini, 2016), a research was developed to better simulate and define the mathematical formulation of the geometrical surfaces of pieces produced with AM to minimize the dimensional errors during production using AM technology. In an experimental campaign, it was also possible to achieve a reduction of 70% of the dimensional error characteristics of the traditional method.

Another paper focused on the minimization of the geometrical errors due to thermal effects (Béraud, Vignat, Villeneuve, & Dendievel, 2014) from the deposition of the melted materials. A resolution by a new method for the modulation of laser power using a different positioning of the laser beam was suggested. Zha and Anand (2015) investigated the geometrical errors of the cylindrical shape by considering the passage from the CAD model to the triangular shape for stereo-lithography. They built a new procedure to minimize it.

In a very different sector, such as medical products, there is also a high interest on the research on dimensional and geometrical tolerances. However, to date, few studies were developed specifically for such research. Moreover, only one study was found in the international literature, which was published in 2015; this paper performed a sensitivity analysis on several possible causes of the dimensional and geometrical errors that are possible in the production of this particular type of object (Pinto et al., 2015). The main problems recognized are as follows: (i) the image acquisition and printing resolution, (ii) triangulation resolution and (iii) segmentation threshold. Once the main problems are recognized, it is believed that the errors could be minimized by choosing better triangulation and printing resolutions. However, there is an important need for modifying the segmentation algorithms of these standard procedures.

From these papers, it is quite clear that the theme of the tolerances achievable using AM technology is a deeply investigated theme and good results have been derived from this theme, thus applying AM to industrial purposes that uses these tolerances of work for defining the achievable quality parameters possible. Other efforts have to be made to cover the lacks in these mechanical sectors; however, it is possible to understand that this theme is developed to let the practitioners consider AM technology to be capable of producing parts with a medium level of geometrical and dimensional tolerances.

Once the papers were analysed, they will be analysed and referred to the mechanical properties of the materials produced with the AM technology.

In general, it is possible to say that any metal that can be welded is usable for AM processes. Many steels, e.g. stainless and tool steels; titanium and its alloys; Ni-base alloys; some Al alloys and Co–Cr have been used in modern AM machines. Nevertheless, it is important to cite the availability of Cu-based powders that are capable of realizing products with high capability of electrical conductivity. Therefore, it is possible to say that the metal AM nowadays covers many metals. However, it should be noted that alloys that crack under high solidification rates are not good candidates for modern laser sintering machines. Moreover, it is possible to say that something has changed in the purchasing sector of these powders with the modern laser sintering machines, with which it is no more needed to use specific powders developed specifically for them.

The evolution of the materials that can be used for AM technologies was demonstrated by many papers available online. In fact, in 2006, Santos et al. demonstrated that the stainless steel and Ti–6Al–4V products realized with different machines and different types of powders were not comparable with the traditionally used materials (Santos, Shiomi, Osakada, & Laoui, 2006). In addition, in the following years, the attention paid to metals used in AM remained high as witnessed from a study reported by Murr et al. (2012) on the capacity of the new laser sintering and electron beam melting (EBM) machines that produce metal products of high quality (Murr et al., 2012).

The problem with the materials used in AM production systems has been investigated for many years. In this paper, we will mainly try to determine the achievements of the material technology for the industrial sectors of machining metallic products and metallic aerospace products by principally focussing on the materials cited before, which are titanium alloy Ti–6Al–4V, AlSi10 Mg and some stainless steels.

This material is very appreciated in many aerospace and mechanical applications. In fact, as it is reported in a work published in 2015, the alloy Ti-6Al-4V is capable of reducing the *buy-to-fly* index from a typical value of 15 to 1 for the aerospace industry (Szost et al., 2016). This index is the ratio between the weight of the raw materials and the weight of the components at the end of their production. For Ti-6Al-4V, by using an EBM method, it is possible to achieve a deposition rate of 500 mm/s with a moderate operational cost (even if from the papers analysed, it is not so easy to understand what moderate means in terms of numerical approach if compared to other technological methods of production). In the paper by Szost et al. (2016), the following defects for the EBM are reported:

- (1) lack of melting and
- (2) high porosity of the materials (i.e. the gas captured inside the melted materials).

The problem of porosity of the materials that are produced using AM technology is a very important issue. This problem has been evident since 2011 when Baufeld, Brandl, and Van der Biest (2011) published a paper. In this paper, a limit of 6% was stated for the porosity of materials to avoid gas from being captured in the material. If the porosity crosses this limit, the material loses its mechanical characteristics in a very remarkable mode. This element is very important because a specific value to judge the quality level of a part produced with EBM technology is defined.

The paper by Zhao et al. (2016) examined the theme of the definition of the mechanical characteristics of the alloy Ti-6Al-4V, reported the results of several mechanical tests and compared the products produced with this material and that manufactured using two different technologies of production: the laser-beam deposition (LBD) and the shaped metal deposition (SMD). In particular, it is interesting that for both the products it is not present any particular remark about the comparison with the traditional ones. The products have a critical break tension of 900–1,000 MPa, and a starting tension for the plastic behaviour of 770 MPa. The paper cites as possible improvement of the mechanical characteristics the possibility to work the material with a thermal treatment to reinforce the material. Moreover, in the paper, a possible improvement was reported in the costing and sustainability of the production process when compared to traditional processes, even if this comparison is not translated in numbers.

The production methods, such as the EBM and the LBD, and the SMD characteristics are summarized in the following Table 1.

To strengthen the impact of what was depicted in the paragraphs above, we refer to a paper that was published in 2015 (Shiva, Palani, Mishra, Paul, & Kukreja, 2015) on the mechanical properties of the alloy Ni-Ti (used in several sectors such as automotive, aerospace, biomedicine and robotics) that was produced using the technology of shaped memory alloy (SMA). In their paper, several controls are performed and are described as follows:

Table 1. Machine production parameters used for EBM, LBD and SMD by Baufeld et al. (2011)

	EBM	LBD	SMD
Maximum power	3 kW	3.5 kW	2.2 kW
Maximum welding velocity	16.0 mm/s	10.0 mm/s	5.0 mm/s
Maximum wire-feed velocity	25 mm/s	40 mm/s	33 mm/s
Maximum wire diameter	1.0 mm	1.2 mm	1.2 mm
Maximum height deposition step	0.1 mm	1 mm	1 mm
Maximum deposition rate	0.1 kg/h	0.7 kg/h	0.6 kg/h
Maximum wall thickness	10 mm	4–5 mm	9.1 mm

- (1) Scanning electron microscopy,
- (2) Differential scanning calorimeter,
- (3) X-ray diffraction and
- (4) Micro-hardness test.

In all the tests, the products produced with the Ni-Ti alloy using SMA presented behaviours similar to the ones produced using traditional methods, confirming the suitability of AM methods.

Another issue of AM is the problem related to the control methods for the identification of defects in the products. The paper by Cerniglia, Scafidi, Pantano, and Rudlin (2015) analysed the techniques used to identify the flaws inside the products produced using laser powder deposition (LPD) technique, which is widely used for the rapid manufacturing of parts or for the production of high-value spare parts. The method proposed in their paper to analyse the defects online during the production process is validated and demonstrated to be effective.

Another proof of the reliability of the products obtained with AM, even if not belonging to the metallic materials or to the titanium alloy category, is mentioned in the paper by Yang, Harrysson, West, and Cormier (2015), which demonstrates the honeycomb auxetic and re-entrant structure realized with organic materials with AM technology and presents the same mechanical characteristics of the ones produced with the traditional methods.

Another material used in the AM technology is AlSi10 Mg, which is a non-metallic material. Moreover, we observed that the products obtained by the traditional methods and the ones produced using AM exhibit similar mechanical characteristics. The production process analysed in the paper is direct metal laser sintering. Moreover, the mechanical characteristics of products using direct metal laser sintering are totally comparable with the ones of the using traditional processes (Yan et al., 2015).

In addition, there are many papers that investigated the capacity of stainless steel to produce objects with similar characteristics as the products produced using traditional processes. Cormier, Harrysson, and West (2004) studied the mechanical resistance of the H13 stainless steel, and a similar work was performed by Murr et al. (2012) for the PH20 stainless steel. The results of these studies demonstrated the possibility to compare the mechanical characteristics of the materials produced using AM with those produced using stainless steel and traditional processes.

A final confirmation of what was reported before, which proves that the AM technology is capable of producing materials that are sometimes better than the previous cast or sand-cast materials, is given by the study of Guo and Leu (2013). In the study, they reported the mechanical tests for the materials previously discussed (Ti-6Al-4V, stainless steel, etc.) and others (Co-Cr alloy, IN625, Co-Cr-Mo, etc.). The mechanical characteristics (ultimate tensile strength, yield tensile strength, elongation and elastic modulus) for all of these materials are better than the reference values (Guo & Leu, 2013).

From the literature analysis on the mechanical characteristics of the materials operating with AM technology, it is quite evident that these materials have characteristics that are comparable with those of the materials produced using traditional processes, except for some defects on the porosity of the materials.

Another very important issue to demonstrate the process capability of AM is the geometrical complexity of the products.

In conventional manufacturing systems (subtractive, formative and joining processes), engineers and designers are trained in design for manufacturing and assembly. In this context, complexity is

excluded from design: complexity of the shape implies an increase of machining steps, more tool paths or expensive custom tooling (Conner et al., 2014). As stated by Edmonds (1995), complexity affects a multitude of aspects. For this reason, in conventional manufacturing, there is a direct link between production costs and shape complexity (Hague, Campbell, & Dickens, 2003). Conversely, AM allows us to produce parts, of any complexity of geometry, without the need for tooling (Hague, Mansour, & Saleh, 2004) and without increasing production costs (Lindemann, Jahnke, Moi, & Koch, 2012). Merkt, Hinke, Schleifenbaum, and Voswinkel (2012) suggested that “complexity-for-free” could improve product performance at the same cost. In addition, Gibson, Rosen, and Stucker (2014) discussed AM and its capabilities in comparison with other manufacturing processes. Therefore, it is possible to affirm that AM proves to be better than traditional systems as it overcomes all complexity limitations of traditional systems. According to Rosen (2007), it is possible to define three capability levels of AM:

- Shape complexity: any type of shape is possible to be produced; several sizes of one part are feasible and customization is an easy task, thus enabling shape optimization.
- Material complexity: the material can be differentiated point by point, layer by layer and so on, thus enabling the manufacture of parts with complex material compositions.
- Hierarchical complexity: using the micro-structure with geometrical mesostructure, it is possible to manufacture hierarchical multi-scale structures.

Many authors produced many works on the measurement of complexity. The following are some relevant contributions reported.

Valentan, Brajliah, Drstvensek, and Balic (2008) used the triangles contained in the STL file as a shape complexity index of a part. However, “the utility of such measure is limited given that the mesh density can be varied by processing software or user input” (Conner et al., 2014).

Joshi and Ravi (2010) defined a shape complexity factor using geometrical information of a part. They defined five criteria based on the number of cores, volume ratio, area ratio, thickness ratio and depth ratio. Previous criteria are weighted using a regression analysis on 40 industrial parts.

Psarra and Grajewski (2001) defined, for 2D shapes, the degree of convexity of the perimeter as an index of the complexity of a shape. They defined an index named mean connectivity value (MCV), defined as the “percentage of locations that is connected without crossing a boundary or falling outside the area of the shape”. This method was used to define the complexity index of floor plans of buildings. Baumers, Tuck, Wildman, Ashcroft, and Hague (2016) noted that for layer-by-layer processes, it is possible to transfer the Psarra and Grajewski approach to a 3D solid object geometry because in AM processes, “a continuous 3D solid is split in a sequence of 2D layers”. Baumers calculated the MCV for each layer and studied the correlation between shape complexity and energy consumption for EBM. Moreover, he observed that for AM, the correlation between shape complexity and energy consumption is small. Furthermore, there is a direct link between cross-sectional area and energy consumption.

An evolution of the simple measurement issue is constituted by the decision support system based on the complexity issue. For example, Conner et al. (2014) defined a decision support system based on complexity, customization and production volume to facilitate product development decisions. Moreover, they suggested that part complexity depends on the number of features a part contains, their location and their geometry. Their approach replicated the one used by Joshi and Ravi (2010), but they reduced the number of criteria adopted.

We see that the complexity in AM plays a fundamental role in the possibility for this new technology to be adopted in the industrial context, giving the possibility to pass beyond the traditional limitations of shaping given by the traditional manufacturing systems. In fact, this issue was investigated by many authors to determine methods to enable the managers to adopt the right level of complexity in the design of new parts.

Therefore, in conclusion, technologically speaking, the AM processes are fully reliable to be included in a more general production flow, thus giving a new strength to the design of the parts because AM is complexity free.

3.2. Literature review on management issues for AM

As stated above, the technological and quality issues, i.e. the capability, for AM are quite advanced to be applied in an industrial cycle. Therefore, let us present a deeper issue about AM, that is, the management issue.

Since the beginning of the new century, the theme of the integration of AM in the industrial context of production was researched, for example, the study by Lee and Woo (2000). Since then, many other studies were performed in this field, trying to bring a novel technology in the field of management of industrial systems (Atzeni & Salmi, 2012; Berumen, Bechmann, Lindner, Kruth, & Craeghs, 2010; Hague et al., 2003; Hopkinson, Hague, & Dickens, 2006; Khajavi, Partanen, & Holmström, 2014). The management issues were focused on many years ago. However, it is not possible to say that the theme is closed. In our opinion, this is due to the fact that the themes related to management have to be developed after a deep investigation on the cost control systems for AM, and other basic researches on the theme have to be developed.

Before focussing on these issues, we tried to understand in general, what is the state of the art of other operation management themes.

For the purpose of this paper, 45 papers from several journals of the main scientific database available these days were analysed.

The relevance of AM in operation management and, especially, on the life cycle of the products was foreseen since the research by Gäbel, Forsberg, and Tillman (2004) and Morrow, Qi, Kim, Mazumder, and Skerlos (2007).

Other initiatives on the themes of AM in operation management are present in the field of organization in the starting phases of the life cycle, i.e. the design (Gäbel et al., 2004; Hague et al., 2004; Rosen, 2007).

However, no sources were present in the initial years the 20th century on the other operation management issues such as business and cost models, supply chain management and planning models.

The first contribution on production convenience is possible to be identified by the paper by Karunakaran, Suryakumar, Pushpa, and Akula (2010). In this paper, they treated the metallic materials produced with AM in a rapid prototyping context. The result of the paper is that it is possible to find many advantages from the AM application. In fact, it is demonstrated that the AM technology allowed the dramatic reduction of the production costs for a single product.

Another contribution published by a research group in 2010 investigated the sustainability impact of a production using AM (Sreenivasan, Goel, & Bourell, 2010). No comparison with the traditional methods to produce metallic parts was performed in the paper. However, an assessment framework for sustainability evaluation for an AM performed with a laser synthesizing technology is presented considering the following facets: (i) the energy consumption, (ii) waste generation, (iii) water usage and (iv) environmental impact.

The importance of AM in the industrial context became more evident as many studies were proposed on the general theme of the AM application in the industrial context. Furthermore, many authors started to publish on these themes.

In particular, in many authors, the possibility to change the perspective of the design in the value chain of industrial companies arose strongly owing to many contributions (Atzeni & Salmi, 2012; Klahn, Leutenecker, & Meboldt, 2015; Ranjan, Samant, & Anand, 2015; Wong & Hernandez, 2012).

Moreover, a lot of research projects were granted in this field in these years; thus, we can see that many research and knowledge dissemination projects were presented in many countries such as the USA and in Europe (see the US National Science Foundation and the European CORDIS).

In 2013, some papers on AM operation research theme were published. In 2013, a consistent step forward was conducted by a US research group, which published an interesting study about a convenience analysis between traditional and AM methods for rapid prototyping (RP) performed with the life cycle cost (LCC) typical framework (Wittbrodt et al., 2013). At the end of this study, the convenience of AM for RP by analysing the pay-back period (PBP) and the return on investment (ROI) indexes was demonstrated. Other authors started to investigate the environmental impact of AM on the production of the pieces, which can be produced with this new technology (i.e. AM). In a paper by a US research group, the energy cost and, in general, the LCC associated with the pieces produced in the aircraft industries using AM were studied. In particular, the impact of AM on the design and production phase for the parts of aircrafts is examined, finding a remarkable reduction of the cost during the life cycle time span (Huang et al., 2015). The environmental issues of AM are related not only to production processes but also to life cycle assessment of the products in their life cycle time span as it is proposed in a research paper by a German research group (Burkhart & Aurich, 2015). Many others can be identified on this issue since 2012 (Bechmann, 2014; Belkadi, Bernard, & Laroche, 2015; Burkhart & Aurich, 2015; Chen et al., 2015; Cozmei & Caloian, 2012; Gebler, Schoot Uiterkamp, & Visser, 2014; Giret, Trentesaux, & Prabhu, 2015; Gupta, Laubscher, Davim, & Jain, 2016; Huang et al., 2015; Le Bourhis, Kerbrat, Dembinski, Hascoet, & Mognol, 2014; Nyamekye, Leino, Piili, & Salminen, 2015; Petek Gursel, Masanet, Horvath, & Stadel, 2014; Würtz, Lasi, & Morar, 2015).

In 2014, another study was published that proved the convenience of an AM technology for the production of parts and analysed how the supply chain for the same product can change if a traditional or AM technology is considered for production (Achillas, Aidonis, Iakovou, Thymianidis, & Tzetzis, 2015). A decision framework was depicted to decide if this technology is applicable to a specific product, and good results were found to justify the use of AM for industrial production of complex shaped products or prototypes. After 2014, other papers on the supply chain management issues related to AM were published (Barz, Buer, & Haasis, 2016; Bogers, Hadar, & Bilberg, 2016; Emelogu, Marufuzzaman, Thompson, Shamsaei, & Bian, 2016; Gress & Kalafsky, 2015; Jia, Wang, Mustafee, & Hao, 2016; Khajavi et al., 2014; Mellor, Hao, & Zhang, 2014; Nyamekye et al., 2015; Pinkerton, 2016; Weller, Kleer, & Piller, 2015).

Another aspect that was investigated was concerning the business models and the cost evaluation models to apply AM in the industrial context. In 2014, another implementation framework for AM technology was proposed by another research group (Mellor et al., 2014). In this paper, the authors tried to understand, from a bottom-up approach, which of the more suitable sectors for the application of this new technology are used as judgement parameters: (i) the AM technology for production performances, (ii) the impact of AM on supply chain, (iii) the impact of AM on the organization, (iv) the impact of AM on operations and (v) strategy. The objective of this paper was to furnish to the product or project developer a tool to assess in the right way possible future products or new possible way of business. Another paper that underlined the convenience to use AM in modern production schemes was published in 2015 by a US–Chinese research group, which demonstrated the convenience of AM considering the supply chain and LCC (Gao et al., 2015). Another framework that

is useful in deciding whether or not to adopt AM for the production of selected parts or pieces was also published in 2014 (Conner et al., 2014). This framework is based on the evaluation of the following parameters: (i) complexity of the piece to be realized, (ii) production volumes and (iii) level of customization of the product. By using these three elements, it is possible to place a point in a three-dimensional graph and to understand the possibility whether or not to apply the AM technology. The framework in this paper is useful in understanding the main management issues related to AM adoption better. In 2015, papers on the economic implications of the application of AM to a production company were published (Weller et al., 2015). A deep economic analysis was performed in the paper, and a payoff function usable by the company that utilizes AM was shown. This paper deeply investigated to gauge the main economic variables related to the specific AM theme, such as the marginal costs of the production and the quality issue impacts on production economics. Another paper on the economic issues related to the industrial application of AM was presented in 2015 by a German research group that investigated the possibility to build a cost function for the adoption of AM technology (Schröder, Falk, & Schmitt, 2015). The economic theme was also examined by other publications in the same year, which tried to define a model to measure the performances and the real status of the production processes applying AM (Baumers, Dickens, Tuck, & Hague, 2016). In the paper by Baumers et al., the fact that AM is not a technology for large volumes of production is underlined and justified by theoretical reasons. Moreover, in 2015, a research paper on the creation of a decision support system that is able to position at the right level of a complex bill of materials of a specific AM part by minimizing the LCC and maximizing the value chain related to the final product was published (Würtz et al., 2015). In 2015, another research work was published to help practitioners to implement AM in standard production systems (Hedrick, Urbanic, & Burford, 2015). In particular, the paper dealt with identifying and resolving the main issues to facilitate AM implementation. These issues mainly refer to the operation management issues, to identify the most critical issues to reduce the problems and to manage the operations for the materials and production operations. Other operational themes related to the AM technology were examined to understand the production cost for the creation of the selling price in pre-order phase. In a paper published in 2015, which applied a model of the grey theory, a selling price is easily calculated to help sellers in selling products created using AM (Zhang, Bernard, Valenzuela, & Karunakaran, 2015). Many other authors investigated the theme of the business models, decision support systems and cost evaluation models in the recent years (Achillas et al., 2015; Lim et al., 2012; Manogharan, Wysk, & Harrysson, 2016; Piili et al., 2015; Rickenbacher, Spierings, & Wegener, 2013; Weller et al., 2015). Another management themes discussed in the scientific literature concerning AM was the possibility to integrate AM productions with the traditional ones (subtractive technologies), developing new integration frameworks possibly capable of reinforcing the power of AM and offering a mid-step for the final substitution of traditional methods with AM in production systems (Newman, Zhu, Dhokia, & Shokrani, 2015).

Therefore, it is possible to conclude that AM has been facing management issues since 2010. However, effective contributions are provided since 2013, when some papers on the possibility to analyse AM from the perspective of costs and management were published. After 2013, the number of papers in this field began to increase exponentially (see Figure 1).

Nevertheless, it is quite obvious from the analysed publications that the theme of AM management is not very well covered and examined, thereby missing a systematic approach to cost and management in general. In fact, this missing objective is quite evident to be understood from Figure 2, where the number of papers that examine a specific operation management theme is reported. In this figure, the themes are very different and many. However, in our opinion, more missing issues are mainly related to a reliable model for cost evaluation, which could not only be useful in the design phase of production systems with AM but also in the management phase design. This opinion is also shared with the scientific community, which is focusing on the operation business models and costing systems.

The problem in the fact that this management issue is not much developed could be due to the absence of a model that is able to appropriately measure the process in which the AM is present.

Figure 1. Number of operation management publications per year.

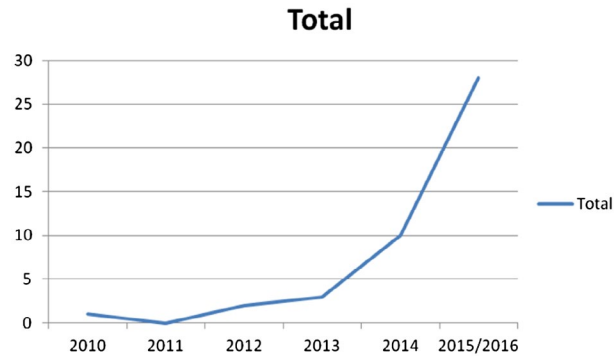
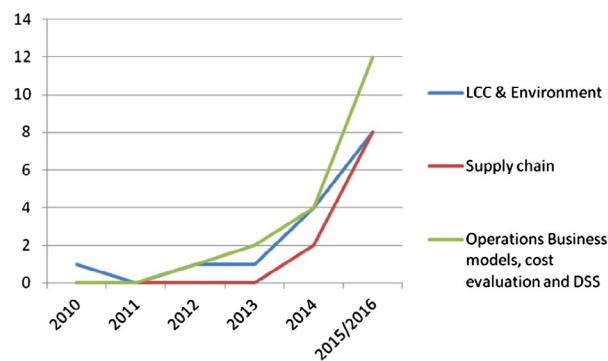


Figure 2. Number of publications for operation management in AM per year and per theme.



Devising an appropriate cost model could be the first essential step than all the other issues related to more a sensible management such as sustainability, supply chain and scheduling operation problems. All of these themes are very important, but they can be applied only when the system is measurable. A reliable model for the cost evaluation of a production with AM integrated with the traditional processes or separated from the subtractive ones probably represents the best way to cover a very important issue, which so far was not covered by much impacting approaches.

Nevertheless, it is important to note that AM and its impact on production industrial systems have yet to be examined by thinking about the change of perspective about the raw material stocks; appropriate time for purchasing stocks and the safety issues related to the introduction of a technology such as AM, which is an unattended process but has several risks such as explosion and fire.

4. Conclusions

In this paper, we attempted to analyse and categorize the themes related to the production issues of AM technology. The AM technology began to become an industrial solution recently. Thus, it was recognized as an interesting theme with a possibility of deepening the research area if this technology achieves a good level of maturity in terms of mechanical resistance characteristics and achievable tolerances. After the first step analysis, the state of the researches on the operation management field was analysed and investigated.

This paper defined a precise method for literature review, and it analysed and categorized several papers with the method introduced before.

From the literature analysis conducted, it was quite clear from technological and production quality levels (measured from the capability to achieve such levels of geometrical and dimensional tolerances) that not so many issues are open. Thus, it is possible to conclude that AM is quite ready to be applied in the industrial context, given some adjustments that are still needed on the processes to

avoid the porosity problems for the parts processed using the AM technology and to achieve some geometrical tolerance such as concentricity and circularity. Therefore, the metal pieces can be directly realized using the AM technology, with a good level of reliability of the part, when the pieces are under mechanical stress. Moreover, the parts realized in this way are good in terms of tolerances achievable, limiting the need of mechanical post-processing activities.

Starting from this result in this paper, it was investigated if scientific literature lacks the possibilities of AM to be a production technology in the industrial world. In fact, to make real the possibility to effectively bring this technology in the production context, it is required that AM becomes a theme studied and known from the operation management point of view, also offering the possibility to be measured in a production context. In fact, the technology is evolving, and it is necessary to understand the production management issue. Therefore, it is possible to say that if a lot of work was performed and good results are available from the point of view of mechanical tolerances and properties, the same cannot be said from the management point of view. Therefore, this state of the art can be the first point of study of an important issue about the methods to measure the process costs when the AM technology is used to produce an item.

Moreover, as argued in the previous paragraph, the management theme seems to be affected by a very important absence. Many authors started studying the management issues related to general systems; however, nobody recognized the main limit in the actual knowledge level. In fact, so far, no effective contribution on the cost modelling of the production systems that want to use the AM technology as a principle or part of a more general system of production has been reported.

Therefore, it is possible to individuate as the main issue of operation management not only the themes introduced before and briefly reported in Figure 2 but also the theme of the construction of a reliable cost model to make a production system measurable, which is characterized by the presence of an AM machine. This need is also evident from the fact that the cost modelling was examined so far from a very limited number of papers, demonstrating that the researches about this theme are at the beginning and trying to categorize the system (Baumers, Tuck, Bourell, Sreenivasan, & Hague, 2011; Hopkinson & Dickens, 2003; Manogharan et al., 2016; Ruffo & Hague, 2007; Schröder et al., 2015).

Therefore, it is possible to conclude that the operation management issues and, in particular, the theme about the cost model for AM in the industrial field are new research topics and need more attention. There is a need to develop new research contexts and find optimizing solutions for this new way to produce parts of complex systems such as cars, airplanes and oil and gas drilling parts.

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Corrigendum

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