Benefits and costs of additive manufacturing applications: an evaluation guideline

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Abstract: With an ever growing diffusion of additive manufacturing (AM) system in industrial and consumer level, as well as the direct and indirect dynamics which are being introduced resulting from its inclusion as a viable production system on companies' portfolio, the need to reconfigure production system and adapt the production line becomes even more relevant than before. There are several studies which have emphasized on the importance of a paradigm shift in order to exploit advantages of AM, not only considering design and functionality of the product but also with regards to its impact on the entire value chain reconfiguration. Thus, it is of crucial importance to take into consideration that for this shift to be feasible and manageable, it needs to include both technical and managerial aspects of manufacturing. This work proposes a new perspective to provide a guideline for the proper evaluation of AM implementation from a holistic viewpoint. Starting from a *priori* analysis, the authors provide a three-steps evaluation guideline, thanks to which companies interested in additive manufacturing could verify both technical and economical feasibility of its implementation, comparing it to the conventional subtractive techniques. The proposed guideline is tested in real case study, which the main results are shown in section 5.

Keywords: Additive Manufacturing, Assessment guideline, Case study

1. Introduction

Considering their evolution rate, Additive Manufacturing (AM) technologies are becoming more interesting for a huge spectrum of industries and the applications will soon impact also the production activities of components and products [1]. AM is subjected to a dual trend: from a non-scientific point of view, it manifests an overflow of available data; from a scientific standpoint, the literature is often not sufficient for the practical evaluation of these techniques, lacking specific guidelines that can help non-experts attain the necessary know-how. The authors have found that the scarce available literature is not aligned with companies' requirements which are focusing mostly on technological aspects and without providing an holistic view that ensure the evaluation of all the benefits and limitations of AM. In order to highlight the main limitations, three categories have been identified:

i. The data provided are often not up to date (and generally refer to a particular technology or even to a particular machine);

ii. The majority of the works consider a specific technology, and do not provide a priori analysis for identifying which is the most suitable for the context of application;

iii. As a consequence of point ii, the economic analysis generally does not com-pare different technologies to evaluate which is the best one. Considering that each technology encompasses several machines (by different manufacturers), this would lead to a significant limitation of the proposed analysis;

iv. According to the point iii, the models compare production costs, but do not consider the investment decision analysis.

In order to overcome the shortcomings described above, this work provides a holistic guideline for evaluating proper use of AM technologies. The main objectives can be summarized as following:

- To define a guideline to support manufacturing companies to understand whether AM techniques are suitable for their context and products, proposing criteria valuable for an a priori analysis, and providing a list of the (eventual) appropriate technologies and related machines;
- To provide a model for the evaluation of the economical convenience of AM application, compared to the conventional subtractive technique.

2. AM System

In order to have a better understanding of AM, it is necessary to look at it from the system point of view. This is due to the wide range of impacts that is accompanied by its implementation: extending from raw material suppliers and procurement, towards production level, distributors and even customers. A systematic analysis allows for characterization of the system to address all of its attributes. AM, just like any other kind of manufacturing system has its own cons and pros and thus, a rigorous investigation of its mechanism is required. AM is a term applied to a technological class which consists of multiple subsets that make up the technological variations. Each of these technologies could be applied in various industries ranging from consumer goods to medical and aerospace.

2.1 AM Characterization

One of the most remarkable aspects of AM which has enhanced its position among other manufacturing techniques is the flexibility which not only enables economical low volume production [2] by eliminating the need for tooling, but also provides product designers with a degree of freedom that no more limits functionality in favour of feasibility of the process. This feature provides manufacturers with two remarkable opportunities regarding the design: faster time-to-market, and almost real-time design changes that happen as improvements and optimizations are made to the original design.

According to [3], special features of AM would result in the following benefits:

- No tooling is required,
- Economic production of small batches becomes feasible,
- High flexibility for changing the design of the parts/products,
- Optimization for product functionality would be achievable,
- Products and design customization which are based on individual customers' needs,
- High possibilities of wastes elimination during production phase,
- Possibility of having simpler and shorter supply chains.

Another study [4] characterizes AM by highlighting its distinguishing features. High automation and part consolidation which provides the possibility to build parts as a single piece and therefore eliminate the assembly would consequently lead to a great reduction of the labor, storage, handling and logistics costs. Economies of scale are one of the most remarkable properties of mass manufacturing. Manufacturing in large volumes allows for reduction of cost per unit as a result of the fixed-cost proration. However, since AM machinery requires no setups, production in small batches becomes economically feasible and this is a direct result of economies of one.

Economic inefficiency in large volume production, inability of processing large parts due to the chamber size limitations [5], process variability [4] and lack of consistency among produced parts to ensure mechanical properties of the parts [6], incompetency of the companies who are struggling with process automation and digitalization, limited range of raw materials and lack of international standardization are amongst the most important barriers towards considering AM as manufacturing method

2.2 AM technology variations

Different approaches have been introduced to classify AM processes. One classification is based on the raw materials feed. Accordingly, the processes can be divided into the classes which use four types of input raw materials[6]: polymers, metals, ceramics and composites. Another type of categorization is based on the working principle of process: liquid, filament/paste, powder, and solid sheet [6]. Yet another type of classification is based on the "method to fuse matter on a molecular level" and consists of: thermal, UV light, laser or electron beam. Finally, there is another classification of process technology which is introduced by ASTM F42 committee.

The notable areas in which AM has been deployed with high rates of success are currently limited to medical devices, consumer goods (e.g. electronics), aerospace, automotive, jewelry, architecture and defense [2]. Although various studies have considered the issue of energy usage in AM machines, a unified and standard procedure to measure energy consumption is still lacking and there needs to be more data for making comparisons among conventional technologies and AM. However, there are multiple studies [7] which show when it comes to the environmental aspects and carbon footprint, AM has a positive impact. Needless to say that a majority of these researches would still pinpoint the focus of their investigations into the lack of detailed information regarding wastes, energy consumption and environmental impacts.

3. Impactful dynamics of AM

As it was mentioned earlier, AM is a system which is attributed by a variety of dynamics. One of these attributes which directly impacts the value chain is the supply chain management. The ability to redesign products with fewer components and the possibility of manufacturing products near the customers' physical location are two opportunities offered by AM [5]. This would not only reduce the need for warehousing, transportation and inventory turnover, but it would also make the supply chain simpler by reducing the time-to-market and lead-time. Design for Additive Manufacturing (DFAM) is a term which is used to emphasize on the flexible aspect of AM; meaning that since there are no limitations imposed by the design of the product to reduce its functionality, parts can be redesigned into single components and thus, AM's capabilities would be exploited in a more efficient way. By doing so, a reduction of the materials, energy and natural resources would take place which would eventually result in significant sustainable and economic benefits. An exciting area for AM to implement is in the spare parts supply chain. A thorough investigation [8] of spare parts supply in aircraft industry shows that rapid manufacturing (which is a term used for AM of individual parts/small lot sizes) can be used for low volume production of parts in a centralized location and at the place of consumption, if inventory holding and logistics costs are high in comparison with the production costs. This strategy would keep stock level down and AM capacity utilization high. In another study [9] four scenarios were studied in two dimensions of supply chain configuration (centralized and decentralized) and AM machine technology (current and future technology). One significant outcome of the study showed that with the current maturity of AM in which machines are both capital- and labour intensive, centralized production is more efficient, while with the evolution of technology in the future, characterized by cheaper and more automated machines, distribution of production would be a better choice for the spare parts supply chain.

Although lack of enough supporting data to measure sustainability aspects of AM is a big impediment to research, some researchers have tried to identify the key concepts of AM which are relevant to sustainable manufacturing [7]. These are the same advantages that distinguish AM from conventional and traditional manufacturing processes. Considering the current legislation and regulatory laws that exist on the environmental aspects of manufacturing processes, and manufacturers' tendency towards moving to cleaner and more sustainable production, the environmental impacts of AM is part and parcel of any analytic assessment. An analytic model on the evaluation of environmental impacts in AM [10] which considered the whole environmental flows, shows that in order to study the global environmental impacts, not only the electricity power consumption, but also the materials, and fluid consumption need to be taken into account.

4. State-of-the-art of AM adoption frameworks

With the increased relevance of AM, nowadays researchers are putting more efforts in the identification of a costing model that computes the production costs of each AM technique and processes [19].

One of the first contributions in this research stream comes from [11] that provided a model for estimating the cost of AM applications. It analysed the direct cost of production considering the machine, labour, and material costs, omitting the overhead costs and also the energy consumption. One of the most relevant outputs of the work has been the evaluation of the typical 3D printing cost profile, not dependent on the quantity produced. In some following studies this result is discussed more deeply and confuted especially for small production batches.

The use of activity-based costing for the economic analysis of an AM alternative is provided in [12] however the proposed model had strong limitation since it considers one single technique. Although, [12] confirmed the previous assumption, stating that the more production chamber is saturated, the more the unit cost production is reduced. The models provided in the following years [13]&[20] try to evaluate the cost of 3D printing application in an holistic view, considering a life cycle approach. In these works, the authors encompassed also re-designing activities which are required for a full exploitation of 3D printing capabilities, and incorporate full advantages enabled by AM. The approach considered by [14] is one of the most comprehensive ones: first, they identified a list of possible products that may be revisited by AM, for each of which, they then evaluated the most appropriate technology that matches the firm's requirements, and only at the end of this evaluation process the authors developed an economic analysis.

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Considering a more consultancy-oriented approach, one has to notice the work of Senvol (included in [1]), an American company which experts in AM machinery and applications. In the paragraph titled "Cost-Benefit Analyses for Final Production Parts", the authors explain applications of their cost evaluation model. Contrary to the previous works described above (e.g. [11] & [12]), their model does not provide a constant production cost, because of the inefficiencies caused by print batches. So, until the printing chamber is not completely saturated, the production cost per part provided is not constant. Considering the assumption that the more the machine is saturated, the lower the final production cost per part, previous scientific works that hypothesize to fully load the printer capacity seem more attractive. This assumption is reasonable taking into account that a company could saturate the printer with the production of some prototypes of other components or products (due to the absence of setup cost) and so working with a fully saturated printer chamber.

5. Evaluation guideline and case study

According to [15], nowadays companies need more support in order to evaluate whether or not AM could be suitable for their activities and products, and academics have to propose guidelines that help "senior management to reconsider whether they will continue using current production technologies, or they could benefit by exploiting the benefits of modern AM technologies". In accordance with this statement, the authors have identified a logical path that a company approaching AM for the first time could follow for a comprehensive evaluation of the AM techniques (Figure 1).

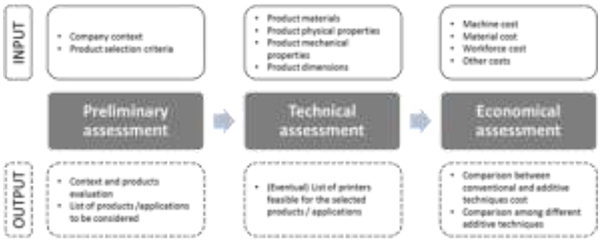

Figure 1 - Proposed AM evaluation framework

Considering the main lacks described in the introduction, the guideline aims to provide a complete assessment of this new paradigm, considering not only an economic evaluation or a context/product analysis but also a comprehensive assessment of the alternative AM technologies that can be employed. The text provides an a priori analysis of the AM applications, considering the main features of the company context and products properties, and then proposes a technical and economic model to provide data for a quantitative assessment.

5.1 Preliminary assessment

The first step that a company should perform to understand whether these technologies may bring advantages to its business is a preliminary (qualitative) assessment of the context in which operates.[16] provided a framework that encompasses three key attributes: production volume, customization, and complexity of the products. Simkin and Wang of Senvol [1] proposed 7 different scenarios that "lend themselves well to AM". These scenarios consider elements that range from manufacturing cost, required lead time, inventory cost, supplies risk, logistics cost and finally to the need to develop products with improved functionalities. When a product falls into (at least) one of these categories, a more precise assessment is warranted. Also [16] provided a framework that encompasses three key attributes: production volume, customization, and complexity of the products.

The works cited do not provide quantitative drivers for an easy evaluation of which products are more promising for AM. Indeed, it is argued that already in this preliminary step a company should consider indicators related both to product and supply chain features for identifying which products (or range of products) could be encompassed in the following evaluation steps. For this reason, four different quantitative drivers are introduced that permit a selection of the most promising products for AM:

- Cost weight intensity = (Product overall cost [€])/(Product weight [kg])(1)
- Buy to fly = (Total material consumption [kg])/(Product weight [kg])(2)
- Mould cost intensity = (Cost of the mould allocated to the product [€])/(Product overall cost [€])(3)
- CNC time intensity = (CNC time consumption [h])/(Product volume [⟦dm⟧^3])(4)

5.2 Technical assessment

The next evaluation phase takes the input from selected products of the last stage, aiming at evaluation of the technological feasibility to manufacture them through AM. A more quantitative analysis is performed in order to map some relevant product features that have to be considered in this technological assessment: dimensions, materials, physical and mechanical properties, and so forth. The comparison of these parameters with a machines' database ensures to identify the (eventual) technologies and the related machines that are suitable for the company's products and needs. The output of this step is a list of (technology and) machines that fulfil the company's requirements, along with information about the machines price and the resellers that could provide it.

5.3 Economical assessment

By identifying the list of feasible machines, it is possible to perform a preliminary evaluation of the cost occurred by the company. The provided tool aims to overcome the general lack of the existing model described in literature:

i. The model takes in account all the data collected in the technical database, considering the 108 printers categorized. The real value of the previous database consists in the amount of data collected that enables the economic cost evaluation for (at most) all of the different technologies and printers.

ii. The model considers the investment required to purchase a specific printers and encompasses this cost element in the analysis performed.

The developed model ensures to perform two different types of analysis: one for evaluating if products or components made by AM are more cost-effective than the same products or components realized through conventional subtractive techniques (injection molding or CNC machining), and the other one for evaluating which of the different AM technologies (or printers) that fulfill company's needs is more cost-effective, overcoming a general limitation of the literature. According to [11], the provided model computes the direct cost of the AM application in terms of machine, materials and workforce. Indeed, thanks to the rigorous data collection, the cost related to the maintenance activities that [12] took into account as indirect cost, is considered to be a direct cost.

5.4 Case study

The proposed case study considers a company that has exploited AM since 2001, and reached a high level of knowledge especially on SLA. The company belongs to the automotive sector (specialized in the production of racing components), and operates following an Engineer-To-Order strategy in a one of a kind production context.

According to the holistic guideline described before, the company context is first considered for a preliminary analysis. After the positive qualitative results, the proper technologies for the specific requirements are identified and then an economic analysis of the selected technologies (and printers) is performed.

The company context immediately appeared highly suitable for AM applications, due to the high products complexity and customization, as well as the low volumes of production:

- for the majority of the products realized, the buy-to-fly ratio is very high (exploiting conventional casting and molding technologies) according to the hollow structure required;
- considering the uniqueness of the products, the mold cost intensity is also very high, in accordance with the allocation of the mold cost to only one product manufactured.

Throughout the technical assessment, it has been possible to identify which technologies are feasible for company's activities. Taking into account the main technical features, as products' dimensions, surface finish, mechanical properties (all these data were collected through interviews directed to R&D manager), the technical database is consulted to exhaust all the available options. Not surprisingly, the output provides 15 printers belonging to SLA (6 of them) and SLS technologies (9 of them), both evaluated by the company in 2001.

In the remainder of the paper two simulations (even though 15 simulations were originally developed according to the output of technical assessment) are shown: one for the SLA (the iPro800 printer which is the actual one adopted by the company), in order to validate the model (considering the actual adopted printers), and one for the SLS to evaluate an alternative scenario (considering the most advanced printers coming from previous step, that is the Spro140 HD by 3D Systems). It has to be noted that for SLA, the mod-el output approximate the actual cost given by the company with high accuracy (accuracy > 95%). The comparison of SLS and SLA highlights lower overall cost for SLS, with a global saving of more than 300.000 € per year (about 25% of reduction). In Figure 2 the cost structure for as-is and to-be scenarios is illustrated.

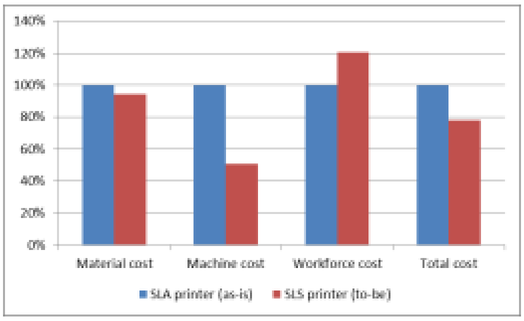

Figure 2 - Economical analysis of as-is and to-be scenarios

- Material cost is lower for SLS considering that the higher waste rate of the technology is balanced with the cost per kilogram of raw material, which is roughly half compared to SLA.
- Machine cost is higher for SLA, and constituted the majority of the gap between the overall costs of the two technologies. This is due to the stacking parameter: SLA does not permit to stack up different products on different layers, while SLS (that exploits powder material) ensures to fully saturate the printing chamber with different layers of products. For this reason SLA technology requires more printers to fulfill the annual demand of products than SLS. In particular, SLA requires 6 printers while SLS needs only 2.
- Work cost is similar for the two technologies. SLS requires more time for finishing operations, while SLA requires longer time for the setup activities.

6. Conclusion

The majority of the existing manufacturing frameworks, that are applied for the manufacturing technology selection, stem from the past technologies, some of them dating as far back as mass manufacturing techniques. The current trend of production technology characterized by fast pace and dynamic changes is subjected to multiple variables and uncertainties. There are two points about AM that draws a lot of attention among concerning researchers in the field. First, the rather young age of AM compared with the traditional and conventional technologies and second, the ongoing process towards its full adoption as a manufacturing system in the industrial world. However, it must be noted that due to the incomplete maturity and ongoing research, many of AM's aspects including, but not limited, to process measurement and standardization, finish surface quality, throughput rate, raw material selection, still lack enough competence to replace conventional technologies and become a widely accepted manufacturing system among industrialists. Additive manufacturing is subjected to a dual trend. So, from a non-scientific point of view manifests an overflow of available data, and the media treat every kind of possible applications and often are too enthusiasts about 3D printing, making everything seems easy; from a scientific standpoint, the literature is often not sufficient for the practical evaluation of these techniques, lacking of specific guidelines that can help non-experts attain the necessary know-how [18]. These elements create relevant gaps between company's needs and available data and models. In order to overcome the lacks described above, this work provides an holistic model for evaluating properly the use of additive manufacturing technologies.

There are at least two different directions for further development of the work:

- In order to define a more holistic approach to AM, it is necessary to develop more case studies and accurate tests of the guideline, in order to identify threshold values for the described four drivers to immediately discriminate which products should be subjected to a technical and economic evaluation and which should be excluded through further analysis. Thanks to this further development, the entire evaluation process time will be cut significantly.

- It should be considered that, due to the rapid growth and evolution of 3D printing market and technologies, the printers database exploited for the technical feasibility evaluation, must be constantly updated. The data concerning printing speed, surface finishing quality and mechanical properties related to 3D printed products are often not available and based on assumptions of the authors.

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