Evaluation of technical and economic feasibility of additive manufacturing technology: evidences from a case study

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Abstract: 3D Printing has been firstly licensed in the far 1980 year by Charles Hull, the founder and (still) president of 3D Systems, which is a leading company in this sector. The technology has followed an incubation period of almost 25-30 years before becoming enough mature to propose a big spectrum of printing techniques, usable materials which allowed to cross the boundaries of traditional prototyping activities, fully soaking in the direct production of parts, components and final products. The main aim of this work is to test and validate an empirical guideline and tools thanks to which every manufacturing company can evaluate whether additive manufacturing (AM) applications could be suitable according to their specific context. Guidelines and tools, coming from a previous work developed by Pour et al. (2015), have been properly updated and integrated, thanks to a new application in a case study involving a large enterprise, belonging to the textile machinery sector.

Keywords: Additive Manufacturing, Assessment guideline, Case study

1. Introduction

Considering ASTM definition, 3D printing is: “… a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies”. Just looking at this definition, it is easy to understand that 3D printing belong to the Additive Manufacturing (AM) techniques. Different terms can be used for the AM processes according to the field of applications such as: Rapid Manufacturing (RM), Rapid Prototyping (RP), Rapid Tooling (RT). Despite the use of these different terms, the building process of a product represents the key distinguish figure of these technologies: in fact, additive processes build objects layer-by-layer, adding materials, rather than through molding or subtractive techniques (such as machining) that remove materials.

Due to the novelty of AM paradigms, the competencies and skills available within companies for evaluating the implementation of AM systems are still low and enterprises need support in order to evaluate whether or not AM could be suitable for their production processes and products Achillas et al. (2014). Moreover, this lack of credible and impartial experts, represent one the most important inhibitory factors for the deployment of these new technologies within the companies. According to recent practice-oriented surveys (developed by Gartner, McKinsey, BCG, etc.), this lack of specific skills and guidelines limit companies in achieving the necessary know-how Lipson and Kurman (2013).

To provide a fist step into closing this gap, giving also a contribution to existing literature, this work exploits the map proposed by Pour et al. (2015) with the following aims:

- To enlarge the current body of literature that deals with existing tools valuable to support companies in the evaluation process of technical and economic feasibility of AM techniques;
- To apply and test the provided guideline in a second case study (the first is in Pour et al. (2015)), with the main objective to verify the comparison among traditional and AM techniques.

2. AM applications, benefits and limitations

The AM technologies can have diversified impacts according to the field of applications. In general, the main benefits are related to the reduction of production cost and time compression for the realization of complex and personalized products with respect to traditional manufacturing methods Atzeni and Salmi (2012) & Atzeni et al. (2010). Other benefits are related to the increased quality of developed products, the higher level of flexibility and rapidness for manufacturing activities, and the possibility to modify the supply chain configurations. These benefits can be grouped into 6 different classes that are briefly described in the following:

- Small volume production

In case of small production volume, 3D printing applications can allow to save costs. In fact, components produced by injection moulding or die casting require expensive tools and mould, that implies high fixed cost that can account for more than the 90% of the overall production costs (especially for small batches). For the subtractive methods, the unitary production cost depends on the quantity produced, while for 3D printing, the unitary cost is considered constant Hopkinson and Dicknes (2003), due to the absence of tools and mould that are no longer required.
• Material waste reduction

AM materials have higher cost compared to traditional ones, but the overall material cost of a product manufactured by AM process could be lower than the traditional ones thanks to the capability to reduce the scrap rate of different types of products. A commonly used indicator of the material use efficiency is the buy to fly ratio, which is the ratio between the weight of the material used and the weight of the final product. When this ratio is high for traditional processes, AM could generate savings thanks to its ability to manufacture with a buy to fly ratio closed to 1 (Allen (2006)).

• Elimination of assembly operations

The freeform design that characterizes the AM processes enables the reconfiguration of manufacturing processes (Atzeni and Salmi (2012) & Atzeni et al. (2010)). For example, companies can reduce the assembly activities, thanks to the possibility to manufacture 3D printing products in a single piece instead of requiring several components to be assembled.

• Easy customization

There is a general law applicable for 3D printing application: complexity and personalization are for free. Thus, the more a product is complex, the more is promising to reduce the cost by AM. With traditional techniques, the manufacturing cost is strictly related to the complexity of the shape of the product. Instead, exploiting AM, the production costs are only marginally affected by the increase in the complexity of the shapes (Hopkinson and Dicknes (2003)).

• Quick new product development

The possibility to test different product configurations could bring big enormous advantages in the time to market for new products (Achillas et al. (2014) & Conner et al. (2014)). With the rapid prototyping techniques, the development of new product is faster, since the engineer could test the product in few days instead of waiting for weeks or months that the supplier delivers the prototypes.

• Flexible supply chain

The use of AM can enable a lot of transformation in the supply chain structure, related to the possibility to produce the components everywhere in the world (also very close to the point where the demand occurs), just sending the 3D model. AM technologies, with their ability to produce parts on-demand without tooling and setup, offer an alternative way for OEMs to reduce supply chain costs while at the same time improving the service level (Holmström et al. (2010)).

3. Literature overview

AM is considered convenient for small series of complex pieces and rapid prototyping activities Grimm (2004), but in the last years 3D Printing has become mature not only for prototyping but also for industrial production Gibson et al. (2010). With the increased relevance of 3D printing, nowadays researchers are putting more efforts in the identification of a costing model that compute the production costs of each AM techniques. Despite this, nowadays the literature does not yet provide a set of tools and models that can be used by practitioners to evaluate and compare AM techniques with traditional ones (e.g. Injection molding, CNC machining), evaluating potential economic savings. One of the first contribution comes from Alexander et al. (1998), that proposed a model for the estimation (and comparison) of the production cost by Fused Deposition Modeling (FDM) and Stereolithography (SLA). The model considered the printing and pre and post-processing activities costs (i.e. material loading, printer setup, support material removal), identifying that the production costs was very influenced by the chosen orientation of the pieces in the printer chamber. However, this model had some weaknesses for serial production (among which the limited processes and technology treated), making it valuable only for prototyping activities.

A more detailed model for production activities was proposed by Hopkinson and Dicknes (2003), that analysed the direct cost of production considering the machine costs, labour costs and material costs (omitting the overhead costs and the energy consumption). The proposed model evaluates different AM techniques (SLA, Laser Sintering (LS) and FDM), for the printing of a single piece continuously for a year. One of the most relevant output 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).

Ruffo et al. (2006) provided a more complete framework, proposing the activity-based costing (ABC) methodology for evaluating the 3D Printer product full cost. This model shows that the production costs for low volume depend on the number of pieces produced (this not linear pattern is caused by different sources of inefficiencies during the production process, related to powder waste and printer saturation). The proposed model had strong limitation considering only one single technique as LS. Ruffo et al. (2006) confirmed the previous assumption that the more production chamber is saturated the more the unit cost production is reduced. In recent years Atzeni and Salmi (2012), Atzeni et al. (2010) and Gibson et al. (2010), tried to evaluate 3D printing application costs adopting the Life Cycle Approach (LCA). In these works, the authors encompassed – with different range of adoption – also the re-design activities, required for a fully exploitation of 3D printing capabilities and incorporate the fully advantages enabled by AM. For example the possibility to revise the design of a product in order to obtain a hollow structure, that implies the reduction of weight, can have a substantial impact on product life cycle costs, generating relevant savings in terms of minor fuel consumption in the aerospace industry. Baumers et al (2012) and Baumers et al. (2011) underlined how the capacity utilization rate of the printer is a relevant parameter for the economic evaluations of the different AM techniques, proving also an algorithm to optimize the
products configuration within the build chamber. The costs for laser sintering application may differ up to 30% with different configuration (of the same products).

Rickenbacher et al. (2013) presented a new cost model for Selective Laser Melting (SLM), based on Hopkinson and Dicknes (2003) and Ruffo et al. (2006) models, that take into account adequately all pre- and post-processing operations. These activities are relevant especially if high-quality standards for functional parts have to be achieved.

In the last years the focus has been shifted from a simple operational point of view, to a more strategic perspective. The main aim of this last stream of research is to propose some metrics that can be exploited for an a priori evaluation of which companies businesses and products best fit an AM production. As an example, Achillas et al. (2014) proposed a methodological framework that combined Multi-Criteria Decision Aid (MCDA) and Data Envelopment Analysis (DEA) for the determination of the optimal production strategy according to firm and market characteristics. Also Conner et al. (2014) provided a framework for determining if AM fits with different businesses, evaluating three key attributes: production volume, customization, and complexity of the selected products (range of products).

With a similar perspective, Beiker and Soções (2014) identified a list of possible products that may be revisited by AM production (selected considering the well-established factors as complexity and volume), then they evaluated for each the most appropriate 3D printing technique that match the firm's requirements, and only at the end of this evaluation process the authors developed an economic analysis.

Considering a more consultancy-oriented approach, Senvol (a US company operating in AM context), focused on AM machinery and applications in the US (Wohlers, 2014). In the paragraph titled “Cost-Benefit Analyses for Final Production Parts”, the authors explain the applications of their cost evaluation model. Contrary to the previous works cited earlier (e.g. Hopkinson and Dicknes, 2003 & Ruffo et al., 2006), and due to the inefficiencies caused by print batches, their model does not provide a constant production cost. Thus, 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 is the final production cost per part, the authors argue that, previous scientific works that hypothesize to fully load the printer capacity, seem more attractive. This assumption seems reasonable from a practical point of view, considering that (due to the absence of setup costs) a given company could saturate the build chamber with other parts/products and hence produce with a fully saturated chamber.

4. Evaluation guideline for AM

The evaluation guideline refers to the ones described by Pour et al. (2015), updated to the last technological improvements of AM technologies (Figure 1).

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 Hopkinson and Dicknes (2003), 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 Ruffo et al. (2006) took into account as indirect cost, is considered to be a direct cost. It is also useful to cite 4 indicators provided by Pour et al. (2015), that permits a selection of the most promising products for AM among the companies’ product range:

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

5. Model formulation

The description of the computational model for the economic analysis is reported below. The main cost elements, as shown in Figure 1, are 3:

- Machine cost, related to the total investment required
- Material cost, that refers to the direct and support material consumption
- Workforce cost, directly related to the involvement of operators during setup activities and post-processing activities.

In order to compute the total cost, two primary data are required: the hourly rate of the printer and the printing speed. The total machine year cost is computed as the annual depreciation of the sum of machine and the ancillary equipment costs.

- Machine hourly rate = \( \frac{\text{(Printer cost per year)}}{\text{(Gross production time) [€/h]}} \) \,(5)
- Printer cost per year = \( \frac{\text{(machine price + ancillary equipment)}}{\text{(years of depreciation) [€]}} \) \,(6)

In order to estimate properly the gross production time, it is necessary to calculate the number of printing sessions required to fulfill the printing volume required. It has to be noticed that the number of sessions required (function of the printer chamber volume and its saturation) corresponds to the number of setup and post-processing activities. According to the additive manufacturing technologies features, setups are not dependent by the production mix: setup activities are required before each printing session (loading material, pre-heating the chamber, etc.), independently by the products that will be realized (it is the same value considering a printer saturated with only one product type and a printer saturated with different ones). The building speed is always very difficult to correctly estimate owing to the lack of data, and the considered values come from the experience of the researcher in many projects of 3D printing feasibility assessment.

- Gross production time = \# printed products \times \text{printing speed} + \sum (\#session) \times \text{setup time + post processing time) [h]} \,(7)
- \#session = \( \frac{\text{(# printed products \times product gross volume)}}{\text{(printer chamber volume)}} \) \,(8)

The material cost encompasses both the support & direct material, and the scrap rate. Support materials are not required for all the additive technologies (only for FDM, SLA and Polyjet) and have lower price compared to the material directly implied for the product. The cost of direct material is easy to compute since it depends only on the weight (or volume) of the product and the price of the material. Despite one of the major claims of AM applications is the possibility to reduce the waste of the production processes due to the additive instead of subtractive processes, this cost may be relevant for some specific applications (not reported here for shortness reasons).

- Material cost = \# printed products \times \text{net product volume} \times \text{material price [€]} \,(9)

The workforce cost is computed for each printing session and it refers to the time that the worker(s) is (are) involved with the machine setup or with the handling or finishing tasks of the pieces. The main activities in which the workers are involved are: the machine setup, the products removal from the building chamber (or the plate), the material support removal ad finishing operations.

- Workforce cost = \sum (\#session) \times \text{setup time + post processing time} \times \text{operator hour cost [€]} \,(10)

6. Case study

The proposed guideline has been applied in a company that operates in the machinery sector (manufacturing machines for yarn finishing sector). The company has a turnover over 50 million €, with several production plants in Italy, Pakistan and China and more than 400 employees. The machines are composed by an high number of pieces and the volumes for each class of machines is around 500-1000 per year. The products realized range from standard machine, sold in high volume, to personalized machines, characterized by unitary (or very small) lots.

The company manifests some managerial issues related to the realization of customized machines, also due to the high price associated with the production of single components. 3D printing could help the company to manage this increasing complexity, maintaining relative low price. So, the company aims to reduce the cost of low volume productions, and reduce the time-to-market, primarily acting reducing the time to test of the prototypes. It has to be noticed that, only for prototyping activities, the company already uses a 3D printer (a Binder Jetting printer). In this sector the continuous innovation is considered one key competitive advantage against (in particular) Chinese manufacturer, and also cost reduction is considered a valuable leverage to compete. So, considering the context and the main future company's guidelines, some of the components associated to the customized machines appear potentially feasible for an AM production. More in detail, some of the quantitative driver defined before can be used for evaluating the preliminary feasibility of these components. In particular, the Mold Cost Intensity is quite high, increasing the propensity for some of these parts to be realized in an additive way. Especially for three of them, a complete evaluation has been performed, as shown in Table 1.
The technical assessment is quite simple, considering the products features. The most relevant concerns the materials exploited: in fact, both the production volume and the products dimensions cannot be considered as constraints (all the professional and industrial printers satisfy these requirements). Since the 3 products were produced in two different materials, there are different possibilities:

- To use a FDM machine Fortus 360mc, with ABSi instead of ABS and PA 12 instead of PA 6 (risky);
- To use a FDM machine Fortus 400mc, with ABSi instead of ABS and ULTEM 1010 instead of PA 6;
- To use a SLS printer with PA12 carbon filled for all the products.

Among the evaluated techniques, in the following analysis will be considered the most advanced, related to the Selective Laser Sintering (SLS) printer. The printer price is about 400.000 € and, adding the ancillary equipment needed, the total cost is about 600.000 €. The period of depreciation is 6 years, coherently to the company’s policy. The output focuses on the evaluation of the breakeven point between additive technology and traditional manufacturing.

Figure 2 - Cost comparison for P1

Also considering the high ratios related to the drivers for Product 1, Figure 2 proposes an AM convenience for production lower than 40 pieces. In fact, the cost to realize a piece through an additive production is about 40 €, while the cost associated to an injection molding process is roughly 41 €, considering batch equal to 40 pieces.

Considering Product 2, the economical assessment suggests that the break-even point is positioned between 90 and 95 pieces. Considering that the annual volume is about 100 pieces, the application of 3D printing appears more suitable, even if there is no full affordability.

Figure 3 - Cost comparison for P2

Product 3 is the most expensive to be realized through 3D printing, coherently with its dimension and weight. Due to the price of roughly 500 €/pieces, the break-even point is positioned between 5 and 10 pieces, far from the batch dimension (about 100 pieces). What emerged is that the more the product is large, the lower is the breakeven point.

7. Conclusion

This work is a natural update of Pour et al. (2015). Considering the rapid pace of maturation of the already existent AM techniques (FDM; SLA; etc.) and the born of new ones (e.g. Continuous Liquid Interface Process; Nanoparticles Sintering), it is fundamental to keep updated the data regarding the 3D printers market. For this reason, the technical database of 3D printers which is at the basis of the provided guidelines, collects and stores more than 120 printers, 15 more than in Pour et al. (2015).

This work is also valuable because proposes a new (real) case study, in which the guideline model is tested with the aim to compare traditional and additive techniques, instead to compare just different AM technologies. Future development will concern two different directions: the former concerns the fine tuning of the economical model, thanks to which standardize and speed up the cost evaluation for AM applications; the latter focuses on finding more industrial cases in which test the provided guideline, considering all the other possible AM
technologies. The proposed work, providing an empirical tool to support companies evaluating a new set of technologies, ensures also to overcome the general limitations of skill and competencies that represent the most inhibitory factor for the deployment of these technologies, and fosters the development of specific knowledge within manufacturing enterprises.

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9. References