Simulation Techniques Prioritization for the Additive Manufacturing Integration in Traditional Production Contexts

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ABSTRACT

Additive Manufacturing (AM) is a modern manufacturing approach and it is considered one of the key enabling technologies of Industry 4.0 paradigm. The attractive feature of this technology concerns, mainly, the possibility to build geometrically complex parts in a single step avoiding all the stages of a traditional manufacturing process and, therefore, reducing the production lead time. Originally, this technology was intended for the rapid prototyping. Nowadays the integration of AM in the Traditional Practical Context (TPC) continues to expand and it is emerging as a valid alternative for the production of low size batches that consist of customized products. This work points out the open issues about the spread of AM technologies, especially, in the production of metal parts. Simulation is a strategic method to evaluate the changes caused by the inclusion of this disruptive technology in a conventional shop floor. The Analytic Hierarchy Process (AHP) is used as decision making approach to prioritize the simulation techniques.

Keywords: Production Simulation, Additive Manufacturing Integration, Analytic Hierarchy Process

INTRODUCTION

American Society for Testing and Materials (ASTM) defines AM processes as being capable of "*joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies*". In addition to this definition, ASTM proposes a classification (Standard Terminology for Additive Manufacturing Technologies, 2012) of AM technologies, based on how the layers are built, into seven categories: (i) Vat Photopolymerization; (ii) Material Jetting; (iii) Binder Jetting; (iv) Material Extrusion; (v) Powder Bed Fusion (PBF); (vi) Sheet Lamination and (vii) Direct Energy Deposition. Inside each category, the machines are mainly distinguished by the kind of material they can work with. Every technology has pros and cons in terms of the building process velocity, accuracy and quality of the part, surface roughness and post-processing needs, amount of waste and costs. AM is a general expression to indicate different kind of application as:

- Rapid Manufacturing, that (RM) indicates the production of end-use components achieved through AM machines (Rudgley, 2001);
- Rapid Tooling (RT) refers to the fabrication of tools that support conventional manufacturing proceedings while Rapid Prototyping (RP) represents the most effective technique to validate how good the product is before the series production starts.

This paper considers AM in terms of RM emphasising PBF technologies for metal processing. In these systems a laser (Selective Laser Melting) or an electron beam (Electron beam melting-EBM) melts a limited area of the material powder together in each layer until the part is completely realised. The use of AM leads to technical and economic advantages in many sectors; e.g. in aerospace, which is one of the leading sector for the production of medium-high complexity parts with AM, the utilization of Ti-6Al-4V allows to reduce the *buy-to-fly index* from the common value of 15 to 1. The main feature of AM is the ability to create high customized and very complex component without further tooling or manufacturing costs and in a single step with minimal added processing. In fact, some authors such as Fera et al. (2017) affirm to evaluate the advantage of using AM in a better way, it is feasible to refer to complexity instead of production volume as decision driver. The "complexity for free" allows the designers to imagine

Communications of the ECMS, Volume 33, Issue 1,
Proceedings, ©ECMS Mauro Iacono, Francesco Palmieri,
Marco Gribaudo, Massimo Ficco (Editors)
ISBN: 978-3-937436-65-4/978-3-937436-66-1(CD) ISSN 2522-2414

the product into a single piece without any loss of functionality. Moreover, although high-speed CNC machining manage to cut out an amount of material much faster than AM can add an analogous quantity (according to EPMA (2015) , AM deposition rate for SLM is around 1-3 mm^3/s), the number of machines, setups and stages increase proportionally with complexity and therefore the production lead time grows up. With AM, the manufacturing process of the item requires only a 3D model and raw materials without needing any tool or fixtures. Another crucial aspect in the estimation of AM's economic and managerial benefits is represented by AM machinery capability of producing simultaneously several parts in its build chamber. This feature could lead to an important reduction of inventory management costs (Mani et al. 2014). Despite these positive features, AM is still affected by some technical and operational issues. Problems concerning dimensional and geometrical tolerances (it means a lack of 5-20 microns), anisotropy, low mechanical strength, high surface roughness and porosity involve the necessity of some post-processing treatments (e.g. milling, grinding and polishing techniques) and limit the widespread implementation of AM in the manufacturing systems. On the side of operations management, there are many open issues related to the very high investment costs for AM machines and materials. Changes involving the scheduling of the activities and the supply chain have still not been investigated in depth. Due to the wide range of variables that characterize a manufacturing system, simulation modelling is, probably, the only tool able to solve complex operational problems without disrupt the existing system. The simulation methods most widely used in manufacturing systems are Discrete Event Simulation (DES), System Dynamics (SD) and Agent- Based (AB) Simulation (Seleim et al.,2012). In manufacturing context, simulation helps to understand the system behaviour in order to raise production throughput, minimise production cost or reduce energy consumption (Mounsey et al., 2016). At first, this work presents an analysis of the current literature. It focuses, mainly, on the research that deal about operations management issues. Moreover, the review lists a series of researches about the use of simulation modelling for the development and testing of new manufacturing system. In the second part, since the choice of the best simulation tool is also related to not quantitative issues, it will be used a well known method to prioritize solutions of problems that calls for also qualitative opinions. The method here proposed is the Analytic Hierarchy Process (AHP). It has been used to prioritise the simulation methods in order to select the most suitable for the analysis of changes caused by the integration of a disruptive technology in a TPC.

Literature Review

The adoption of AM technologies was widely investigated in the this decade (Berman, 2012;; Campbell, 2011). The adoption of AM technologies affects each level of production and logistics system (Pour et al., 2016) and have effects on design, manufacturing and supply chain organisations (Holmström et al. 2010):

- Manufacturing: smaller economic batch size and easier design customisation, no need to use additional tools, wastes reduction;
- Design: functional optimisation of product;
- Supply chain: simpler supply chain due a reduced lead time and lower stock levels

Introduction of AM in traditional manufacturing context could modifies all the value creation system processes. Kritzinger et al. (2018) propose a validation tools to analyse the applicability of additive manufacturing to existing productive enterprise. Mellor et al. (2014) have proposed a framework for the implementation of AM. The changes of the company's value chain have been also reported by Ituarte et al. (2016), which demonstrate how the small-series and pre-series production at the manufacturing refinement stages is, today, an effective alternative to the rigid conventional processes. The product and volume flexibility (Spalt & Bauernhansl, 2016) available using AM allow to modify the product's shape at any stage in order to pander the rapid changes in the market. The literature presents several costing models which distinguish themselves, mainly, on the cost structure. First Hopkinson & Dickens (2003) compare laser sintering manufacture cost with those of injection moulding in order to achieve a break-even analysis and to establish when RM is economically suitable. Ruffo et al. (2006) , basing the analysis on a "full costing" estimation, developed a new cost model for laser sintering production intending to fill the gap and the restrictions of the previous one: the model takes into account the chance to produce with AM different parts at the same time in a single build and asses the effects of indirect costs such as machine hour, production overhead, machine costs on the trend of the cost per part vs. production volumes curve . It is necessary to be able to compare the performances of several kinds of AM technologies. Baumers et al. (2013), first, applied a cost model to a DMLS platform, and then (2016) construct another to evaluate the differences in efficiency between EBM and DMLS both in terms of costs incurred in production and consumption of energy. Fera et. al. (2017) establish a cost structure depending on the sequential steps of the construction job and introduce in their model the Overall Equipment Effectiveness (OEE) index in order to ensure the analysis closer to the real operations management issues. This research paves the way for the optimization of production logistics in a mixed environment characterised by the presence of AM machines and traditional ones. Schröder et al. (2015) made a significant research for the determination of the critical parameters on costs architecture of additive manufacturing: the selection of the best AM machines for metal PBF application is the first management decision. The inclusion of AM into a TPC is a subject under constant debate. Mellor et al. (2014) proposed a conceptual framework that takes into account all the external and strategic factors which impact on AM implementation. A decision making framework for the choice of a successful mix of production strategies was suggested by Achillas et al (2015). Zanardini et al. (2015) give a "three-steps" evaluation guideline whose purpose is to help the managers to compere conventional production scenario with another made up of AM machines. An enterprise could be structured on several levels of management and a variation at one of them could have important effects on the others. The simulation is probably the only appropriate tool for the evaluation and control of these dynamics, especially, when the real world is founded on a complex network of elements and a large number of variables are present (Jahangirian et al, 2013). The first important example on the use of simulation for manufacturing systems dates back more than 30 years (Schroer & Tseng, 1988). Today simulation approach can be used to evaluate several kind of issues going from the process design to ergonomics (Caputo et al., 2019). In simulation modelling each method is intended to be applied in a specific range of abstraction levels (Benjamin et al. 1998). System Dynamics (SD) is at the top of this abstraction scale: processes are considered as stocks and the flow between them are described by differential equations (Borshchev & Filippov). DES is at the lowest level of abstraction: the system elements are modelled as "object" whose state changes when a particular "event" takes place (Schriber et al., 2009). DES is supported by many user friendly software such as ARENA (Smith et al. 1994), Flexsim (Krenczyk et al. 2018), SLX. Gatsou et al. (2009) use DES approach to identify the failings of real manufacturing systems. The capability of DES to evaluate the shop-floor performances was demonstrated by Ng et al. (2014) who used a statistical path to identify the main measurement production criteria. Mounsey et al. (2016) used Simio DES software to evaluate the effects caused by the variations of the shift working patterns and the total number of Machine Operators on both the number of good parts built and the unit part cost for three different components made by metal additive manufacturing technologies Agent Based (AB) models are between those of SD and DES: whatever it is self-contained, autonomous and it has a state that change with time and that interacts with other elements of the system could be considered an agent (Mecal & North, 2010). According with this definition, an agent could represent as much a physical item as an entire company and the global behaviour depends on the behaviour rules of many individuals (Borshchev & Filippov). Monostori et al. (2006) explored engineering design, process planning, production scheduling and control; at the end they concluded that AB modelling is an alluring optimisation tool for all domains of manufacturing. Avventuroso et al. (2017) exploited the simulation modelling software Anylogic to build an agent-based simulation model of a FMS made up of 3D-printing stations. Although this research do not deal with metal additive manufacturing, it provides important results with regard to the impact of process constraints as well as the demand variation on the production line throughput. Due to the reduced lead time and to the great level of customisation, most of the researches focus mainly on the opportunity to radically change the supply chain (Chiu, 2016), but not many of them use simulation modelling to analyse scheduling and production planning problems

SIMULATION TECHNIQUES PRIORITIZATION

The literature review show there are few investigations about the exploitation of simulation modelling to assess the performance of a new manufacturing systems made up both of AM technologies and traditional machines. This approach could lead to have numerical models and to get better system awareness, to accelerate production time, to further reduce lead time, to improve productivity and to support decision making activities concerning the choice of the best manufacturing scenario to implement. Although the technology is not enough mature to produce high volume batches of metal parts, there are same important strengths which should be leveraged to radically change the production paradigms. A critical issue, certainly, consists in the balancing of cost factors, because if on the one hand SLM and EBM machines are capital-intensive, on the other the simultaneous production of different components without it needs to execute expensive setups and the opportunity to decouple the fixed cost from production volumes make more economically feasible the production of small batches. Besides the cost evaluation, the inclusion of AM machines in a shop floor modifies the whole production system and, consequently, the production planning and control must be totally reconsidered. In this section the Analytic Hierarchy Process (AHP) has been chosen as decision making quantitative technique to identify the most suitable simulation method (goal) among the three *options* DES, ABS and SD. The AHP is a multi-criteria analysis that allows to take the best decision minimizing the inconsistence of the decision makers' qualitative judgements about a fixed numbers of *criteria*. It enables decision-maker to prioritize a series of alternatives through a combination of qualitative and quantitative evaluations.

Since the aim of this paper is to identify the best simulation method for the analysis of a new concept of shop floor composed of disruptive technologies, the criteria chosen represent some of the most influencing issues in production system's organisation. They are: (i) resource saturation, (ii) queues analysis, (iii) layout design, (iv) cost and time management and (v) material flow. Fig. 1 shows the AHP hierarchical model built for this research. The analysis has been carried out using the decision support software SuperDecision®.

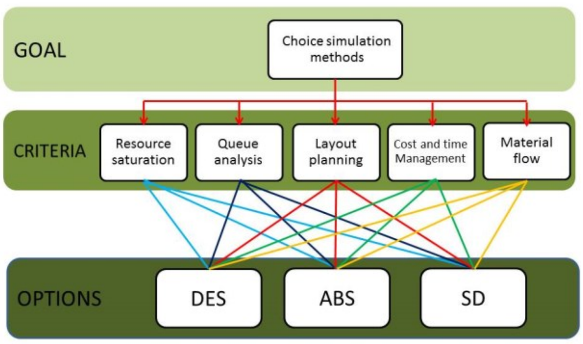

Figure 1: AHP hierarchical model

The method is based on a set of pairwise comparison of the criteria: each couple a_{ij} is scored on a scale of 1 to 9 (Fig. 2) ; the analysis, at the end, gives a weight

VALUE αij	INTERPRETATION
1	i and j are equally important
3	i is slightly more important than j
5	i is quite more important than j
7	i is definitely more important than j
9	i is absolutely more important than j
1/3	i is slightly less important than j
1/5	i is quite less important than j
1/7	i is definitely less important than j
1/9	i is absolutely less important than j

Fig. 2: Rating scale

percentage to the criteria and to the alternatives which means their priority with regard to goal. So, ten experts (researchers, professors and practitioners with at least 5 years of experience in the field of operations management) were asked to express a sets of pairwise comparisons: the criteria compared to the goal, and the alternatives compared to each of five criteria. This means that if the expert rates the couple Resource saturation-Queue analysis with the vote 5, the software considers the Resource saturation is quite more important than Queue analysis with regard to the choice of the simulation method, while a judgment of 1 means they are equivalent. In the second step, judges rates on the effectiveness of an options to another with regard to a specific criterion. To minimize the inconsistency of the judgments, the geometrical mean of the proposed votes for each couple was calculated. The final step is the computation of the priority. The software provides the option ranking based on the entered grades. The following tables show respectively the priorities for the criteria (Table 1) and for the options (Table 2) in term of percentage preference with respect to the goal.

Table 1: Priorities of the criteria related to the goal

Criteria	Preference [%]
Cost and time management	33.21
Material flow	19.18
Layout planning	17.13
Resource saturation	15.39
Queue analysis	15.09

Table 2 : Priorities of the alternatives

Alternatives	Preferences [%]
ABS	41.4
DES	35.5
SD	23.1

DISCUSSION

The AHP analysis revealed that ABS. with a preference of 41.4%, would be the most suitable choice for the decision maker who intends to evaluate which operational and logistic changes are caused by the inclusion of a new production technologies such as Additive Manufacturing. Moreover, the cost and time management was found to be, with an importance of the 33.21 %, the most influential criterion in the choice of the simulation methods. The results agree with we said earlier about the versatility of the Agent Based Simulation. In general AB permits to catch the real dynamics better than SD or DE approach. Nevertheless, AB modelling is harder to develop in a number of applications: it's more efficient to adopt an DES or a SD modelling in these cases. Moreover, the results confirm the attention given by the researcher to the formulation of the cost business model and the definition of the production lead times when a new technology is introduced in an manufacturing system.

CONCLUSION

Starting from the definition of the main issues concerning the introduction of AM in the Traditional Practical Context, in this paper we analysed the state of the art in the evaluation of the economical and managerial effects resulting from the adoption of additive manufacturing, focusing in particular on metal parts production. Moreover, same contributions dealing the application of simulation methods in manufacturing system analysis was mentioned. The analysis showed there are still no researches that deal with the definition of a model for the total inclusion of AM technologies in a TPC. After we have identified same of the most significant operational criteria in a manufacturing system, we have showed how to utilize an AHP hierarchical model for choosing the best simulation methods among the three alternatives DES, ABS and SD. The results obtained with this approach match with the study carried out in connection with the introduction of AM in conventional manufacturing systems. Next step in the research will deal with the demonstration of the substance of this results through the application of an Agent Based Simulation for assessing the practical scenarios in which AM allow to the production companies to get same technical, economical and managerial advantages.

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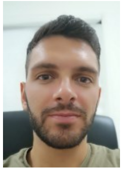

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