PERFORMANCE MONITORING AND CONTROL FOR AN ADDITIVE MANUFACTURING FACTORY - A CASE STUDY IN THE AEROSPACE INDUSTRY

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Abstract

Additive Manufacturing (AM) is a promising technology that opens many new perspectives for design, logistics and production. A few state-of-the art industrial companies are beginning to industrialize this technology, i.e. shifting AM applications from prototyping to the production of end-user parts, and optimizing the production process under standard operational constraints. This shift requires to build and manage high-performance AM-based factories, yet few studies are available about the specificities of managing operations in such kind of contexts. Based on a case study with a leading company in the aerospace industry, we argue that the performance of such AM factories relies mainly on their ability to learn quickly how to control the quality of the parts that are produced and that this requires a customized information system. We then provide detailed descriptions of several operational issues AM factory managers and operators will have to face, as well as corresponding measures and metrics to control the learning process towards designing efficient solutions to these new constraints.

Keywords: Additive Manufacturing, 3D printing, Case study, Performance management

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1 INTRODUCTION

Additive Manufacturing (AM), also called 3D printing, is defined by ASTM as “a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to substractive manufacturing methodologies” (ASTM, 2012). AM is a promising technology that carries a high potential for innovation and opens many new perspectives (Frazier, 2014): designers start exploring new parts geometries that were impossible to build with previous technologies; manufacturing can customize and diversify references more easily; and logistics can be reconceived towards a more decentralized model of production and distribution, closer to the final customers. Those perspectives are reinforced today by the extension of the range of printable materials from plastic to metals and alloys, which broadens the range of AM industrial applications.

Up until now, the primary use of AM has essentially been prototyping. Today rapid progress is being made towards the industrialization of the technology, i.e. producing functional end-user parts, and optimizing the production process under standard operational constraints (e.g. reliability, speed, quality…) Successfully achieving this shift requires designing, building and managing high-performance manufacturing facilities based on additive technologies. Although, building and managing *non-additive* manufacturing factories is a well-studied domain (Hopp and Spearman, 2001) (Ohno, 1988), it is hard (if not impossible) to find any published results on the design of an AM factory. Existing research on AM focuses mainly on improving the technology, characterizing the process from a material science point of view (Gibson et al., 2010) and exploring the implications for design practices (Thompson et al., 2016). Whether there will be any significant changes in the operational management of AM factories is thus an open question.

We present a case study, in collaboration with an industrial company, about the design and implementation of an AM factory producing complex parts for the aerospace industry. We argue, based on the results of this study, that the design of such a factory presents many AM-specific issues that call for customized responses. At this early stage of the industrialisation process of AM technology, the critical factor of performance for an AM based factory is controlling the quality of parts, rather than other usual factors such as cost and delays. Moreover, this consideration for quality should be dealt differently than in traditional non-additive manufacturing systems: monitoring the overall learning and adaptation process of operators becomes the central issue for rapidly transitioning towards optimal operational performance. Monitoring this learning and adaptation process encompasses several activities about which published results and established best practices lack severely. The goal of this paper is to provide helpful insight and guidelines into some of the operational issues companies are likely to face in such projects, by underlining key issues to be dealt with and highlighting broad characteristics of the solutions that can be implemented.

In Section 2, we discuss and analyse the changes AM induces in monitoring and controlling manufacturing performance. Section 3 describes the case study, research methodology and data collection process. Section 4 presents the results of the research: first a generic workflow for AM factories is introduced, then we present a simple model that summarises key constituents of quality management for AM based manufacturing, and finally we discuss in details operational issues and possible solutions based on the industrial case we followed. In Section 5, we conclude.

2 PERFORMANCE CONTROL FOR ADDITIVE MANUFACTURING

Monitoring and controlling manufacturing performance has a long history and well-known best practices. This long-standing tradition is likely to incur a bias in thinking that monitoring the performance of an AM factory is a trivial task that should be rooted in standard methodologies. As we shall argue, while some of the standard performance issues remain valid and a priority, there are subtle differences in their interpretation and additional criteria are needed. The next section presents a brief historical overview of key performance factors for manufacturing systems - in order to clarify which elements, apply and which elements need to be reinterpreted in an AM factory context.

2.1 Costs and delays – significant yet reduced importance

At the origins of manufacturing performance was the seminal work of Frederick Winslow Taylor on Scientific Management (Taylor, 1919). In 1878, while working as a machinist for Midvale Steel Work,

Taylor observed that workmen intentionally restricted their productivity, hence raising the labor costs of the enterprise. He decided to work on this issue, by breaking down workers' activities into basic gestures, timing them, and looking for the best method to do their work (basic operations sequence, adapted tools…). His main objective was minimising costs and delays to increase productivity. The ensuing methodology, called Scientific Management, was widely implemented and resulted in dramatic productivity improvement in many industrial contexts.
Today, even though Taylor's initial conception has largely been subsumed by later approaches (e.g. Lean manufacturing (Ohno, 1988)), minimising costs and delays remains a critical issue in traditional manufacturing systems. However, in an AM context, these criteria need to be reconsidered.
As shown in (Conner et al., 2014), AM is by nature more competitive than other production processes in terms of costs and delays for productions of low volume, high customization and high complexity. This is due to two specific features of the technology: complexity is free and AM machines require no specific tooling and fixture. "Complexity is free" means that while for traditional production processes, costs and delays increase with part complexity, they stay constant with AM, no matter how complex the part. As for the second point, "no tooling and fixture", it is the major source of additional costs and delays for traditional processes when product variety increases. Since they are not needed for AM, this technology is essentially highly efficient for highly diversified production mix.
This type of production to the case we present later, making AM a competitive choice regarding costs and delays. The value of parts produced in this context comes from complex designs that were previously inaccessible: such parts will be high value-added strategic elements within broader and more complex systems, which make costs a secondary factor of performance. Additionally, in such environment, typical projects lifecycles extend over years: delays of a couple of days or even weeks are not a serious issue neither, and they are also secondary compared to quality.

2.2 Quality and adaptability – fundamental issues for AM factories

During the second half of the century started a massive trend for product diversification, which quickly became a key factor of competitiveness (Le Masson et al., 2006). The rate at which new products were introduced increased. For factories operating under heavy cost and delay constraints, these additional requirements amplified the importance of product quality as a significant factor of performance. In fact, a major effect of product diversification is product and process variability - which may cause substantial loss of productivity and reputation. Product diversification also adds to costs and delays since tooling and equipment needs to be renewed regularly.
In addition to the increased demands on costs, delays and quality, two additional aspects became of paramount importance: learning and adaptability. Managers could not rely any longer on a stable product mix to optimize the organization of factories, and rather had to find quick responses to unpredictable and frequent changes in market requirements, dealing with the existing industrial resources and organization in place. The performance was no longer merely achieving acceptable levels on costs-quality-delays, but rather getting there rapidly when product portfolio changed (Figure 1).

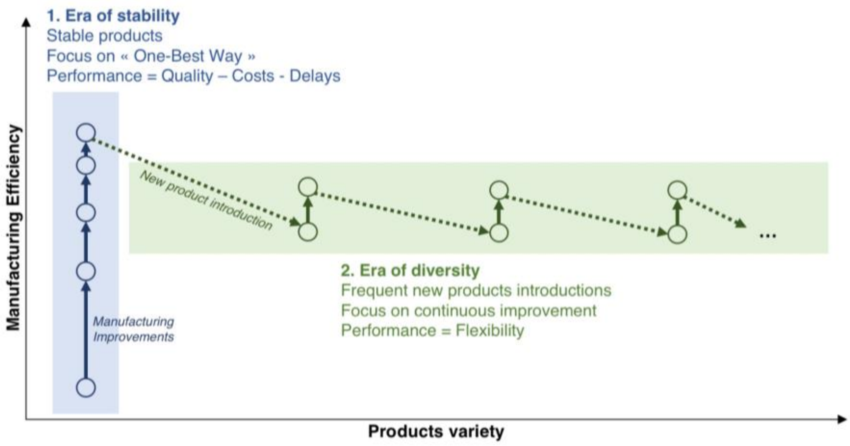

Figure 1. Two eras of manufacturing performance

Current writings about AM present this technology as an effective solution to the variability problem since 3D printing is a generic technology that can be used no matter what part to produce, without the

need to change tooling and equipment. However, this is misleading since 3D printers are complex machines that need to be configured effectively to produce the best result. In this sense, the difficulty to adapt has not disappeared but simply switched to a virtual space, in the machine configuration step.
Beyond machine configuration, several other factors ranging from raw materials to design practices, from effective processing of electronic file formats and transformations to part orientation inside the printer have significant impact on mechanical properties of parts. This is still largely unexplored space and few results are available on each aspect.

2.3 The role of the operator

Taylor's early effort can be seen as an attempt to rationalize the manufacturing process (Hatchuel and Weil, 1995). By relying first on measures, to develop a fact-based understanding of operations, and second on the definition of standards, to generalize good practices among workmen, the objective was to control optimally the operator's performance. This has resulted in the creation of a new class of jobs, the so-called white collar workers, in charge of the organization of operator's labor based on a strong division of tasks between physical and intellectual jobs.
In an AM factory setting this strong distinction wavers since new generation of 3D printers require a complex skill set, which can only be dealt currently by operators that are from an engineering background and even with PhD degrees. Furthermore, most designers so far are not used to design for AM, which also requires that the AM factory operating personnel take on additional roles to maintain feasibility of parts. This is especially true since software used by designers are not fully compatible yet with software used by printers - which incurs additional tasks of verification and conformity control, while managing feasibility and quality issues.
This blurring distinction implies that the learning and adaptation process of the operators of an AM factory is an important bottleneck and a key factor of performance to be monitored. In a sense, this implies a fusion of early rationalisation attempts (such as Taylor's scientific management), and later philosophies (such as lean or agile manufacturing (Gunasekaran, 1999)) that puts the human-centric aspects at the center of manufacturing performance control.

3 CASE DESCRIPTION AND METHODOLOGY

3.1 Case Description – an AM-based multi-unit production

We study the case of an AM factory, designed, built and run by a world-leading industrial company we will call company X, that will print complex metallic parts for the aerospace industry. The facility aims at being both an operational production system, with traditional manufacturing performance objectives, and a center of competence on additive manufacturing, to gain knowledge and expertise on this technology. The factory is still under construction, but is scheduled to start producing parts by the beginning of 2018.
A dimensioning characteristic of the factory is its multi-unit production mix, presenting the following features:

- *High diversity*: all parts are assumed to be different (or produced in very short series of a few samples).
- *High complexity*: the parts produced will be high-value, complex-shape parts, to take full benefit of the geometric freedom offered by the AM technology.
- *Low volume*: the factory is expected to produce between 10 and 50 parts per day when it reaches permanent regime, a few years after starting. At start, production rate objectives are closer to 5 parts per day.

3.2 Collaborative management research

This qualitative research was conducted from February 2016 to May 2016, in the context of a mission led by the consulting firm Manza Consulting for company X, a major industrial company (we do not unveil its name for confidentiality reasons). The present study is based on a collaborative management research (Shani et al., 2008), conducted by researchers and practitioners to create actionable knowledge for the organization and new theoretical models in management research (David and Hatchuel, 2008). The research was performed by two researchers in management science, two Manza Consulting experts in operational performance and the steering committee of enterprise X.

The purpose of this research was to investigate the design of AM factories, to analyse specific challenges resulting from the innovativeness of the process, and propose directions for the development of adequate answers to those challenges. From Manza Consulting's client company perspective, the goal was to explore and anticipate the operational issues they are likely to face when the factory will start to run, hence improving the choices they make in the design stage. From the academic perspective, an AM factory is an interesting and under-studied research object. For the management research community, it represents a new kind of factories, which specificities are to be better described and understood; for the additive manufacturing research community, organizational aspects are an interesting complement to the existing literature which focuses most of the time on the process characterization issue.

3.3 Data collection process and data analysis

Collaborative management research methodology enables access to a large set of data and allows researchers to adjust their investigation to make sense of the field. During our interventions, data has been collected in several ways: interview with key actors (AM specialists, actors from enterprise X…), analysis of existing literature and enterprise X documentation, and participation to regular meetings and working groups. Our study relies on this comprehensive information, although it is not possible for us to present all the exact elements because of confidentiality issues.

Based on this data, we conducted a double analysis to investigate the link between performance and the information system, following respectively a top-down and a bottom-up approach. In the top-down approach, we identified and described several important operational issues that should be monitored for ensuring good progress of the factory's performance. In the bottom-up approach, we focused on identifying potentially needed and available data at the different stages of the process and how to measure and organize this information to answer the AM-specific challenges previously described.

4 OPERATIONAL ISSUES AND KEY MEASURES FOR THE AM FACTORY

4.1 Generic workflow of an AM factory

The following figure presents a summarized description of the factory workflow, i.e. the main stages of the production process (Figure 2).

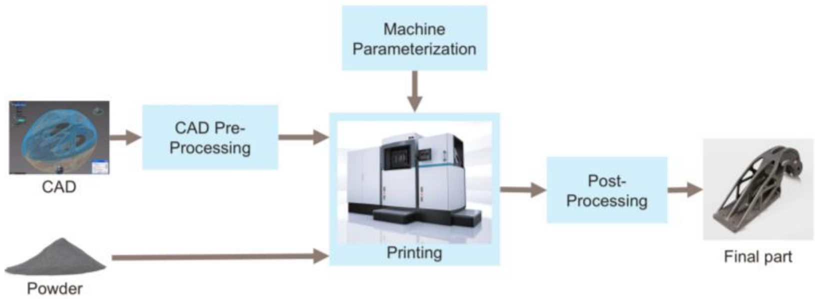

Figure 2. Generic workflow of an AM factory

The production process takes as input metallic powder and a digital mock-up (CAD file) describing the part to print (conjointly with quality specifications, e.g. target geometric, mechanical and physical properties), and must return the printed part with desired specifications. As the previous figure shows, this process can be broken into 4 main stages:

CAD pre-processing: an operator receives and stores CAD files from clients, validates its feasibility on the AM machines, and then operates some transformations to convert the CAD file to a format suitable for printing (e.g. STL format).

Machine parameterization: next, the operator must parameterize the printing process, which is the most critical and difficult operation (all choices made at this stage strongly influence the final quality of the printed part). First, the operator must choose the location and orientation of the part in the build chamber; then add supports to the original part (to ensure that the part will not endure deformations during the printing process); then "slice" the part's digital model into several layers; and finally, set the laser's parameters (most importantly: scanning path, speed and intensity of the laser).

Printing: first, the operator makes sure the AM machine's powder container is filled with the appropriate powder for the build. Then he can start the printing process, and wait for the part to be built, layer by layer. After completion of printing, the machine's build chamber is full of powder, with the printed part in the middle of it. The operator must first remove all the powder using a special vacuum system that will recycle the unused powder for further builds. Finally, he can remove the printing platform from the build chamber, with the part and supports printed on it.

Post-processing: the printed part must then go through some complementary transformations. First, it must be separated from the printing platform and the supports that were added to it for the printing process' sake. Then, depending on the final specifications for the part, it can require a wide range of post-processing operations: heat treatment, surface finish, precision machining… etc. The variety of those operations makes it difficult for an AM factory to insource their whole range, so most AM factory will likely have to manage a network of suppliers for these post-treatment operations.

4.2 Quality management issues and measures for AM Factories

We argued in Section 2 that the performance of the AM factory relies mainly on its ability to control the quality of parts, in the context of a high variety production mix, and that it requires important learning on several aspects of the AM process. Developing a good understanding of the process, and efficient methods to control it, is a highly complex intellectual task involving a high number of parameters. It can only be done through precise and reliable measurement of the phenomena that we want to control (similarly to Taylor's scientific rationalization of operator's physical work in the early 20th century). Therefore, a crucial element of the factory performance is the design of an information system that will be able to describe precisely the different dimensions of the factory that need to be better understood and characterized.

Based on the results of the case study, this section presents a list of important issues that must be better understood by operators for a good control of the factory, as well as corresponding measurement data that will help foster the operators' learning process and monitor its efficiency. We group those elements following the three components that determine the final quality of parts, as shown is Figure 3: powder, CAD, and production operations (printing and post-treatments).

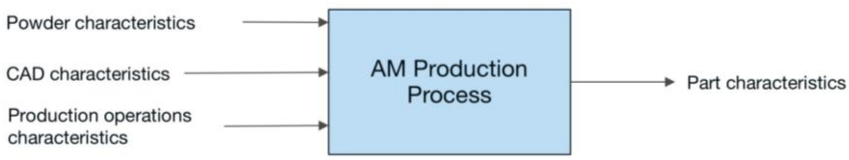

Figure 3. Fundamental model of AM parts quality

4.2.1 Management of powder

Powder is an essential ingredient in the management of the factory's performance and it is important to ensure a good level of traceability of the following aspects.

Reception of powder: at this stage, traditional aspects of traceability must be ensured, recording data like suppliers, operator in charge of receiving the powder, amount of powder received, date of order and reception, state, remarks, etc.

Also, since powder characteristics are a major determinant of final parts quality, powder suppliers must be considered as strategic partners for the factory. Hence, it is important to manage and monitor the quality of the relations with them, e.g. by standardizing the exchanges through common digital tools or conducting semantic analysis of natural language e-mails.

Powder quality test: the AM factory managers must carry out quality tests to measure or confirm the characteristics of powder sold by the suppliers. Characterizing quality of powders is a complex task: traditional methods for material characterization are impractical for AM material in time, effort and cost (Slotwinski and Garboczi, 2015), and powder quality is defined by multiple parameters – an extensive list is provided in (Slotwinski et al., 2014). Hence, designing the test protocols and instrumentation is a major challenge, and AM Factory managers needs to determine which part of those measures can be internalized, and which part should be carried out by specialized partners.

All the data generated by those tests must then be digitized and accessible in the factory's information system, for traceability and analysis. To avoid time waste and errors, this process should be automated as much as possible, using for example image processing techniques to extract features like particles shape or size distribution from microscope images. If performed by a partner, data exchange protocols must be standardized so the information is easily accessible to the factory workers who will try to develop an understanding of the whole AM process.

Powder storage: storage conditions are also important parameters to trace for quality as well as safety reasons (metallic powders can be inflammable/explosive). It will be interesting for the learning process to be able to trace back powder characteristics and storage conditions (temperature, hygrometry, atmosphere composition, time stored…) in case of the detection of non-conformity in the final part.

Powder recycling: during a build, only a fraction of the powder contained in the build chamber is fused and solidified to form the final part. After completion of the printing process, the rest of the powder is vacuumed and recycled in the machine powder container for reuse in later builds.

Though powder recycling is commonly recognized as an economic and environmental necessity, the impact of this operation on powder characteristics remains unclear (Dawes et al., 2015). For a better characterization of this phenomenon, traceability of the powder used is an important issue, as well as sampling and testing the characteristics of the powder directly from the AM machine powder chamber. This traceability requires further investigation about how the AM equipment recycles the powder: when an operator refills the powder container, does the new powder mix with the recycled one or does it stay separated in layers (potentially causing inhomogeneities in the feedstock)? In the latter case, is the first powder sent to the build chamber the new one or the recycled one? After several cycles, keeping trace of the origin of the powder used for the build requires to address those questions. Figure 4 illustrates the composition of the powder in the container in different hypotheses of recycling.

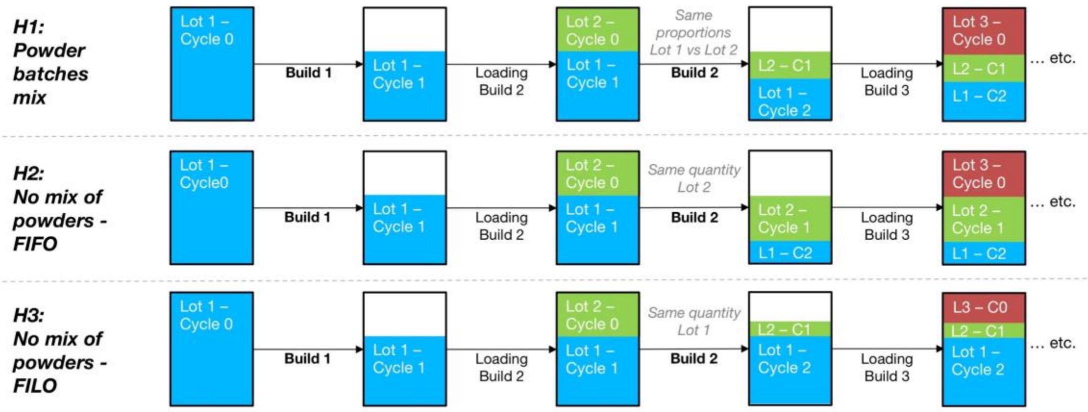

Figure 4. Different models for powder traceability during recycling

4.2.2 Management of CAD files

CAD reception: since AM is relatively new, client design departments are not used to designing for Additive Manufacturing and there are important stakes in being able to effectively explore the new possibilities and constraints offered by this technology (Thompson et al., 2016). This exploration must be conducted at the interface between design departments and the factory's engineering department, which makes the relation between those entities a central point of attention.

Consequently, it will be interesting for the factory to ensure orders traceability (date of reception, client, original CAD files, specifications…), as well as recording all files versions, and try to characterize the maturity of client CAD files, by measuring for example the number of transformations iterations required to convert the initial file into a format suitable for printing.

CAD validation: the first operation the factory operator must perform on order reception will be to assess if the part is feasible or not. Depending on CAD features, quality specifications and operator's experience, either the operator will be able to qualify for sure the part as feasible or not feasible, either he will be uncertain about it. Characterizing the range of feasible and not-feasible designs can be learned by defining key features of the part: forms, mechanical target specifications… (Chen et al., 2015). This process will be an important axis of learning: the more the AM process will be controlled and understood, the more the uncertainty zone will shrink. Figure 5 illustrates this situation.

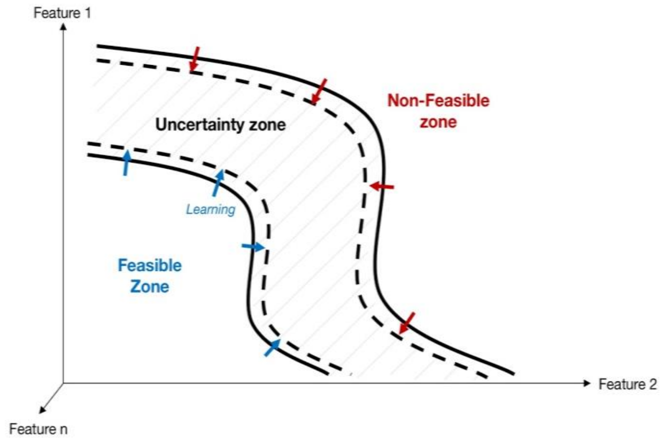

Figure 5. Characterizing feasibility from parts features

CAD transformations: several operations are necessary to convert the initial CAD file from the client into a printable file. These transformations include tessellating the digital model, formatting file, choosing the location of the part in the build chamber, adding supports to the part… This part of the process is in rapid evolution, as software and formats are not yet stabilized (the most commonly used STL format is currently being challenged by new emerging standards like AMF (ISO/ASTM , 2016)).
Those transformations have consequences on the printing process and final parts characteristics, therefore several parameters should be recorded to characterize these relations: for example, tessellation parameters, location of part in the build chamber, orientation or supports added.
CAD storage: an important point for AM Factory's performance is the efficient capitalization on the data gathered from previous production cycles to improve operations efficiency and process understanding. Inference from previous CAD can deliver precious information about the process: impact of a family of forms on part performance, inference of machine parameters from CAD design features, etc.
Therefore, a database of past parts digital models and transformations must be managed as an important asset of the factory. Algorithms that will be able to compare the features of parts recorded in this database will be a desirable tool to improve both the efficiency of these digital transformations (by helping the operator convert a new CAD using results from similar CADs transformed in the past) and the understanding of their impact on part characteristics.

4.2.3 Management of production operations

Nesting parameters: nesting is the operation that consists in printing several parts (identical or different) in the same build, in different locations of the build chamber. Being able to perform this operation will be necessary for improving AM machines throughput, but also has an impact on parts quality. Indeed, it has been demonstrated that location and orientation of part in the build chamber, as well as the addition of supports to the original part, are critical to part final quality (since the printing process is anisotropic). Precise characterization of the phenomenon is still lacking.
Therefore, the factory needs to trace and record the orientation and location of parts in the build chamber, as well as supports position, for further correlation with the characteristics that will be observed on final parts.
Machine parameterization: AM machine parameterization is a key element regarding final parts quality and must be monitored carefully. Principal machine parameters are laser power, speed and diameter, scanning path, and inert gas flow (to control the atmosphere in which the fusion process is performed). It is indispensable to record those parameters for an efficient process characterization.
A key point of attention in this regard will be the relations with AM software vendor: since those essential parameters are set in specific AM-software tools, it is necessary to make sure that they will be recorded, and accessible for extraction, handling and analysis.

Real-time process control and in-process measurements: currently, another problem industrial companies face when industrializing AM is the lack of repeatability of the AM printers. A way to deal with this problem is to improve process control, by implementing real-time control algorithms, based on in-process measurement, as described by NIST researchers in their extensive review of this issue (Mani et al., 2015). Several types of controls have been implemented and tested in scientific literature, but there is no consensus yet on which one proves best.

Since the type of AM process control has significant impact on part quality, the control algorithm that is used must be known and recorded for each build. Also, in-process measurements must be performed, stored and analysed to deliver useful insight on the process. Events occurring during printing can be automatically detected and correlated with final part defaults or characteristics.

Getting access to these parameters requires to engage in a close collaboration with the AM equipment supplier, since measurement instrumentation needs to be added to original machines, which is not a common practice with industrial machinery. Moreover, another important point to be dealt with is the handling of data: in-process measurement can generate a large amount of data (e.g. a camera recording several images per second during the whole build duration - several hours), which calls for appropriate digital solutions that are unusual in such industrial contexts.

Post-processing operations: though they are better characterized than the printing process, post-treatment operations impact the final quality of the part and their parameters also must be recorded (date, operator, recipe…), both for operations performed inside the factory and the ones performed by suppliers.

The collaboration mode with suppliers is an important issue for the AM factory: low volume and high variety of parts can represent a problem of flexibility for suppliers. Moreover, post-treatment operations are critical to costs (they often represent more than half the price of the part) and some sophisticated quality tests on the final part are performed by suppliers. Therefore, maintaining a good relation with strategic partners and organizing collaboration and information sharing will be central determinants of the AM Factory performance.

Final part characterization: characterizing final parts quality is not an easy task: all parts specifications cannot be measured through non-destructive evaluation (NDE) methods (e.g. no such method exist to characterize parts micro-structures, which is proven to influence mechanical properties); moreover, the high variety of products prevents factory managers to apply traditional characterization methods, by sampling identical parts for destructive evaluation and validating the recipe used to produced them (here parts are almost all different, and so is the process to produce them).

Therefore, AM requires new characterization methods. In the short term, test pieces will likely be printed in the same build as real parts, and used for destructive evaluation (by the factory, or its client). This method is not fully satisfactory, because the test piece will not have the same geometry as the real part, and will not have been printed in the same location of the build chamber, which can induce ill-characterized differences between them.

However, gathering precise data about final parts characteristics is fundamental to the development of process knowledge, so all measures available must be recorded in the factory's information system, whether realized internally by factory operators, or externally by specific partners or clients. This requires a particular focus on data exchange between the factory and the other partners that will carry out analyses on the final parts.

5 CONCLUSION

The AM technology is currently taking a big leap from prototyping to manufacturing, which implies designing and building high-performance AM factories. As industrial companies start engaging in this industrialization process, there is a need for exploring the AM-specific operational management issues and designing efficient solutions to help practitioners overcome these barriers. We presented a collaborative management research conducted on a state-of-the-art industrial case with a world-leading company in the aeronautic industry. We argued that the performance of such a factory is defined mainly by its ability control the quality of the parts that are printed, and to quickly adapt to a highly diversified production mix. Developing these abilities requires an efficient learning process based on two critical elements: highly-qualified operators, and a customized information system to monitor the critical points of attention in the factory. We provided, based on industrial field experience, a list of operational issues at different levels of the factory workflow, and some implications for the design of this information system. Further research needs to be conducted to provide fruitful insights to current and future AM factory managers. There are strong needs for improving our understanding of the specificities of managing operations in this kind of context, where both process, equipment and standards are rapidly evolving and not stabilized yet.

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