Development of an economic decision support for the application of Additive Manufacturing in aerospace

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Abstract

Additive Manufacturing offers a high potential in aerospace industry due to its freedom of design and the ability to manufacture complex and lightweight parts. The low number of units, high quality standards and fast response time are special challenges that have to be met especially in the Maintenance, Repair and Overhaul sector. Thus, companies have to decide at which point it is economic to apply Additive Manufacturing. However, companies lack experience on this new technology. This is why a tool is required that takes into account the above mentioned crucial points and supports the decision process. The paper analyzes aviation's characteristics with regard to Additive Manufacturing. The structure of current MRO repair workflows is investigated to identify a feasible application for Additive Manufacturing. Additionally the supply chain will be examined to indicate the benefit which the technology can generate in this highly demanding field. The findings are integrated into a methodology that supports the decision whether to apply Additive Manufacturing on the basis of costs, time and quality.

Introduction

Increasing product complexity and shorter life cycles are major challenge for industry today. To stay competitive companies have to apply innovative technologies to produce individual and customized products. They have to improve quality, costs and time [Mei14]. Due to the layer-based production approach of Additive Manufacturing (AM) this technology offers the opportunity to enhance those key factors. The high flexibility of this technology enables an economic small scale production of highly complex products [Gebh13]. It has the potential to shift the production from a product specific production line to a system that integrates many different production steps.

An environment exhibiting high requirements on time, quality and costs can be found within the Maintenance, Repair and Overhaul (MRO) of aerospace parts. The production and repair of spare parts for aircrafts is demanding and conventional technologies are limited in their ability to meet these requirements without using warehouses as a buffer while AM offers a new scope. [WHY04]

Despite AM's benefits it has to be assessed whether an application is useful for the intended application. Most companies are neither experienced in applying this technology nor in evaluating its utilization. They lack empirical value to calculate the economic impacts in contrast to conventional technologies where a detailed evaluation can be conducted. To compare both, cost drivers for AM have to be identified and associated with further influence factors such as time and quality which are especially important to the aerospace industry [SGF+08].

Therefore an approach is required that takes into account the key factors and determines the most cost-efficient manufacturing strategy. The aim is to recommend an action for an individual decision process. This paper describes a concept for the decision support for metal

AM parts on the basis of the special characteristics of aerospace on a single part comparison. The use case is a defect part that is sent to the workshop in order to determine whether to ‘make or buy’ the part and to specify which technology should be used to do so.

Aerospace and Additive Manufacturing

The aerospace sector will gain importance as forecasts predict. The aerial sector will show a continuous growth in the next decades that exceeds the global growth rate [Boei12]. Nevertheless the piece number of aerospace parts will remain small.
Due to their application field aerospace parts have to meet special requirements. The complex aircraft design often leads to complex parts. Additionally aircrafts have to face extreme environmental conditions that put the part’s requirements on a high level. The rising oil price forces the aircraft manufacturers to develop aircrafts with a higher performance and at the same time a lower fuel consumption to reduce the emissions and overall the operation costs. A decrease in the consumption of raw material during production and in the end a lower aircraft weight is of particular importance for the light weight construction. [Bul09]
For those reasons the use of special materials and manufacturing technologies is often required. In combination with the high quality standards in aeronautics, high unit costs arise. AM is capable to meet these requirements as it offers a flexible production and can manufacture complex parts at nearly no extra costs. Thus it is possible to create lightweight parts with a low input of raw material leading to a low buy-to-fly ratio. This is one reason why the aerospace industry is a pioneer for the application of AM. [GEW13]
However, as the experience with AM is limited in aerospace, the number of additively manufactured parts in aircrafts is comparably low. The certification of those parts is a difficult and long process as it takes time to proof their durability and safety. Nevertheless, companies and research projects such as “RepAIR” are developing concepts to do so. [Rep-ol]
Currently, the focus is on two AM technologies, both metal based: Selective Laser Melting (SLM) by SLM Solutions and Electron Beam Melting (EBM) by Arcam. They are both powder bed based technologies but differ in their energy source. The SLM process uses a laser which is deflected by a scanning unit to melt the metal powder in an inert gas environment to prevent oxidation. For EBM, the energy source for melting the powder is not a laser but induced by an electron beam. The build chamber therefore has to be a vacuum, consequently preventing oxidation as well. The beam is focused and deflected by electric inductors. [Gebh13]

MRO Processes and Supply Chain

The high investment in an aircraft implies that the airline tries to maximize the life time of this investment. MRO providers ensure the airworthy condition of aircrafts and their availability by maintaining all of its components which cause 10-20% of the airline’s overall costs for operating an aircraft [Mens13a].
If a defect is detected then the component is sent to the workshop in order to be repaired if this is feasible. The repair process usually exhibits a generic structure [Mens11] of:

a) inspection
b) cleaning
c) preparing for applying material
d) applying material
e) finishing the part’s geometry
f) coating
g) final testing

In this context AM can be used instead of build-up welding, enabling a much more accurate geometry re-establishment which decreases the effort of further subsequent steps. This is why the whole process has to be taken into account to assess the suitability of an AM application.
A detailed plan to include AM cannot be given, the assessment whether AM is able to compete in time and costs with current repair processes has to be conducted on a single case basis. Besides the economic analysis whether AM can compete in terms of costs with welding for the production or repair, it is also important to consider possible alterations in the supply chain.
The aerospace industry has high demands on the spare part supply chain. It has to be flexible, fast and efficient at the same time to be able to deliver the required part in time to the point of use. In combination with the high value of aerospace parts and the long product life cycle this leads to complex and expensive logistic concepts as part availability and part quality are the major requirements within spare part logistics. [SGF+08] [WHY04]
By nature, the aerospace industry is a global market and there are often labor intensive maintenance checks which are more likely to be conducted in low wage countries which enforce intense competition. Thus, European MRO providers have to search for application fields where they can offer their services competitively. With the help of AM the supply chain process can become more efficient [Fish97]. The batch production and the high set up time cause that conventional manufacturing technologies are not flexible enough to react to a short-term demand. To do so, intensive warehousing is necessary which generates high expenses only due to capital lock-up besides further cost drivers [FrLi09]. Especially parts that are considered as slow-moving can benefit from AM. A conventional batch production is not economic so that a single part can be produced by AM when it is required instead of manufacturing an entire batch and store the surplus parts for a long time until they are inquired.

Production Cost Calculation

The cost calculation is characterized by specific influence factors. It is important to identify those so that they can be evaluated and controlled. The cost drivers can be separated into two groups as figure 1 shows: fixed costs and variable costs. The acquisition of the AM machine and investment in further tools and machines are fixed costs. The amount and extent highly depends on the available facilities and the chosen machine configuration. Costs for maintenance and overhaul have to be taken into account additionally. Occupancy- and labor costs are also independent of single build jobs. One major cost driver of the variable costs is the material usage which depends on the part design. Further variable costs are the operating expenses which are caused by energy and inert gas for the production to prevent the material's reaction with oxygen and a proportion of the overhaul costs. [Gebh13]

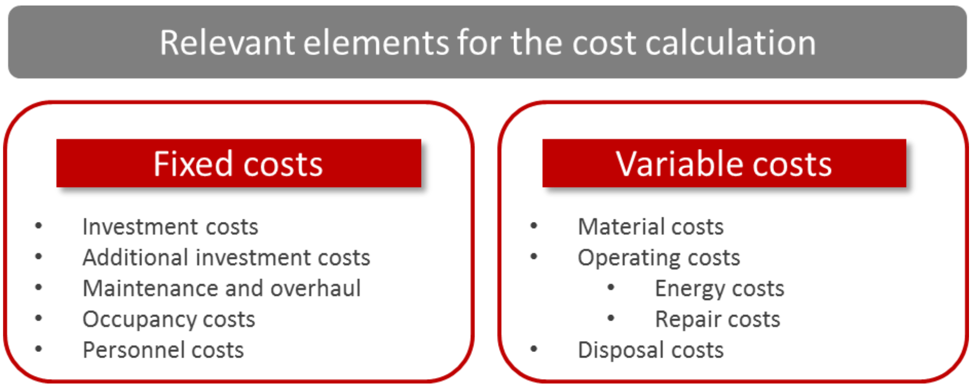

Figure 1: Relevant elements for the cost calculation [Gebh13]

The main influence factors are the build-time, batch size and build chamber utilization rate, the workload, material consumption, process stability, technical progress and service (see figure 2). The build time is one of the key cost drivers and an essential criterion for the assessment of the suitability of this technology for a certain part. It incorporates secondary time for the pre-processing and the set-up of the build job and the AM machine. Due to this fact a high degree of build chamber utilization is preferable to minimize the unit costs as the standard pre- and post-processing activities such as cleaning the machine can be apportioned to more than one part. Nevertheless AM is capable of an economical single part production as the set-up time is considerably lower than the one for conventional manufacturing. In general, the production costs do not decrease proportional to the build chamber utilization rate. Support structures also have to be taken into account, they depend on the part geometry and the chosen material as well as the orientation of the part in the build chamber and increase the material costs. Especially the latter one is another key factor for the production costs as it influences significantly the build and post-processing time. [Gebh13] [LJM+12]

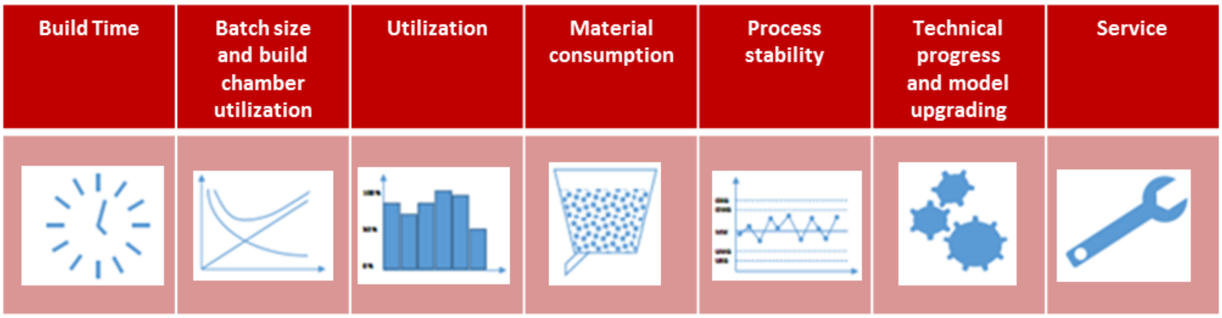

Figure 2: Influence factors of Additive Manufacturing [Fre15]

The flexibility of AM offers the opportunity to use it for several different applications. To remain the flexibility the machines cannot run at full capacity, however, short-term production orders cannot guarantee an optimal workload which is required to be cost-efficient. A trade-off strategy has to be chosen in order to get to an optimal approach. [KPH13]

While AM material is currently comparatively expensive the technology is characterized by a high utilization rate which often compensates the material costs. Additionally, metal powder that has not been solidified during a production run can be recycled and used again [Gebh13]. A critical topic is still the process stability. Quality problems can lead to multiple iterations of a build job and thus leading to high costs. Currently, high efforts for assuring the quality have to be undertaken. Future developments in this field will lead to a much higher part reliability [CCB+14]. This is why the technical progress in the field of AM and its machines is another aspect that has to be considered [LJM+13]. To be able to produce with the most recent technology, high investments are necessary as the technology is fast evolving and updates of hardware and software are usually necessary from time to time. The flexibility of the technology also depends on the service level of the machine manufacturers. If a repair is necessary and neither skilled staff nor spare parts are available, the downtime can lead to unexpected costs and influences the utilization rate negatively.

Decision Alternatives

In order to develop a decision support, the decisions that can be made have to be known. Therefore, the general, operational procedures of MRO provider have to be taken as a basis. If a defect part is inspected at the workshop and classified as not repairable, a new one has to be ordered from the OEM. If a repair is possible it has to be assessed which resources in terms of material, tools and personnel are required. If an economic repair solution can be found, a work order is started. If not, it is checked whether the repair can be outsourced or stored to repair it at a later point of time. [Mens13b]
The decision support in this paper focuses on the selection between three alternatives:

- in-house repair applying AM
- production of a conventional milling part
- the acquisition of a new part

The aim is to develop a concept to calculate a cost-efficient repair. The concept supports the decision process as a standardized instrument to assess the costs of the decisions alternatives and overall saves time and costs during this process. On a strategic level it has to be evaluated if the investment into a new technology is useful to establish a new repair solution.

Configuration relevant subsystems

To calculate the costs for the AM production it is necessary to provide information for different aspects. This is why different subsystems have to be defined. They are divided into four configuration units as figure 3 shows.

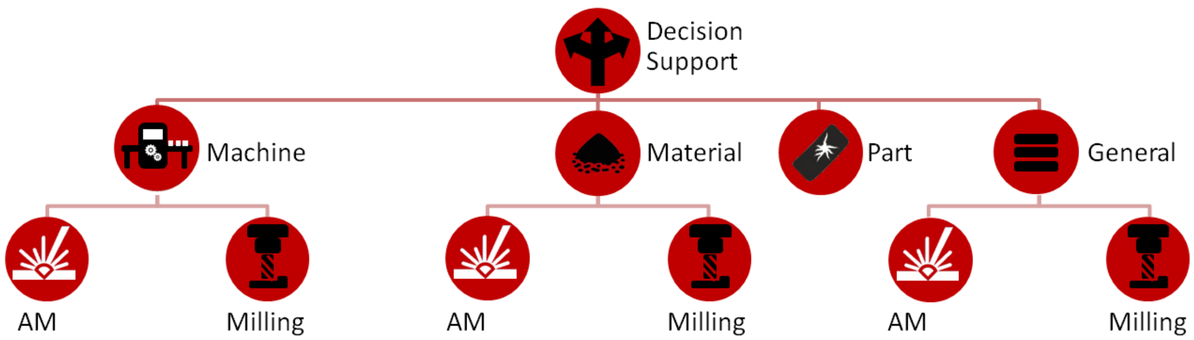

Figure 3: Overview of the configuration units for the Decision Component

They represent separate configuration units which have to be filled by the operator in order to allow the calculation. This process can be supported by pre-defined master data that can be overruled but enables an easier operation of the tool. The system has to consolidate the given inputs and to ensure that all calculation relevant data is available.

Machine configuration
All machine specifications have to be entered in this section. As milling and AM machines differ in their characteristics this has to be done for each separately. The dimensions of the build chamber have to be known so that it can be determined which parts can be repaired. For milling machines the tools have to be indicated. To detail the cost calculation the power consumption can be specified which fosters further potential analyses of the ecological effects.

Material configuration

The configuration of the material is done accordingly. Material for milling and AM can be different if a certain very specific material is not available for one technology, but can be substituted by a similar one. The main focus is on the costs that arise for the repair of a part which is often significant for AM due to the high material prices but can be balanced because of the low buy-to-fly ratio. For AM additional information about the density and a waste factor are required for the calculation. For milling, only the block of solid material is incorporated, using the bounding box as a reference.
Information regarding the supply chain management can be stated, additionally. The availability of raw material has to be ensured. If it is not in stock it has to be ordered from the OEM requiring a certain amount of time which has to be considered when calculating the most cost-efficient repair considering also the time frame. As especially in aerospace time often equals money, this can significantly influence the decision.

Part configuration

The part configuration is not divided into the two categories for AM and milling. Parts can be chosen from a database or they can be described manually by key data required for the calculation. That includes the dimensions of the part in order to assess whether the part fits into the build chamber and the quantity of other parts that can be produced along with it. This is important for the assessment of the machine capacity. The operator has to choose the x,y,z direction accordingly to the part's orientation within the build chamber. The height that has to be reestablishing and the correspondent build up part volume are the major production time determining variables. Thus, they are one of the major cost drivers of the AM calculation. As the prediction of the build-time on the basis of height and part volume is still not accurate for all machines and materials, this can also be filled in manually if a more accurate value is available from former production runs. Additional programming costs can be stated as well. Besides from that a complexity factor has to be chosen for pre-processing the AM build job and for the post-processing effort. There are different ones to choose from. It is differentiated between new and known build jobs and additionally between simple and complex parts all influencing the effort that has to be taken into account for the processing time. Simple and known build jobs can be prepared within a few minutes while complex parts often require a much higher effort for determining orientation and necessary support structure. In terms of the supply chain management the costs for the acquisition of a new part from the OEM can be specified as well as the expected delivery time to compare not only the costs but also the time for the repair and the new procurement.

Others/ general configuration

This subsystem encompasses all other required data which depend on the company. Again, AM and milling are considered differently allowing the separate definition of costs for the two technologies. They can be divided in

I. labor expenses and operating costs
II. hard- and software costs
III. maintenance and production overhead costs
IV. level of capacity
V. depreciation

The labor expenses can be assigned to the manufacturing steps pre-processing, manufacturing and post-processing and are subdivided into wages for blue collar worker, skilled worker and engineers. It is furthermore defined how much manual work each step requires being then

influenced by the complexity factor. Investments for the purchase of machines and software as well as their maintenance expenses have to be filled in. In combination with the annual utilization of the machines and the depreciation time frame the hourly rate for the machines is fixed.
After those inputs have been made once they only have to be updated from time to time as they are not depending on the part or the machine and remain stable for a longer period of time.

The presented system is now able to calculate the costs for an AM production and the milling of a part while taking into account the supply chain aspect whether one option will take longer than the other.

Evaluation subsystem
To provide information as a basis for the decision of a repair or procurement a detailed, yet significant evaluation has to be available. A graphical overview of the calculation results facilitates the decision showing which cost driver is dominating each technology. The share of each of them with regard to the overall costs is important to identify potentials and deficits in the process for further improvements. The illustration of the results into quality, costs and time graphs reflects the fundamental approach every economic oriented company requires. Especially for MRO service providers these three aspects are crucial for conducting their business successfully [Mei14]. The graphs enable the examination of the relations between quality, costs and time (QCT) for the different choices taking more than just the costs into account. They are displayed in percent with 100% for the best rated process option of all calculated repair alternatives. The QCT graphs show clearly which repair alternative offers the best overall solution in terms of cost, quality and processing time.

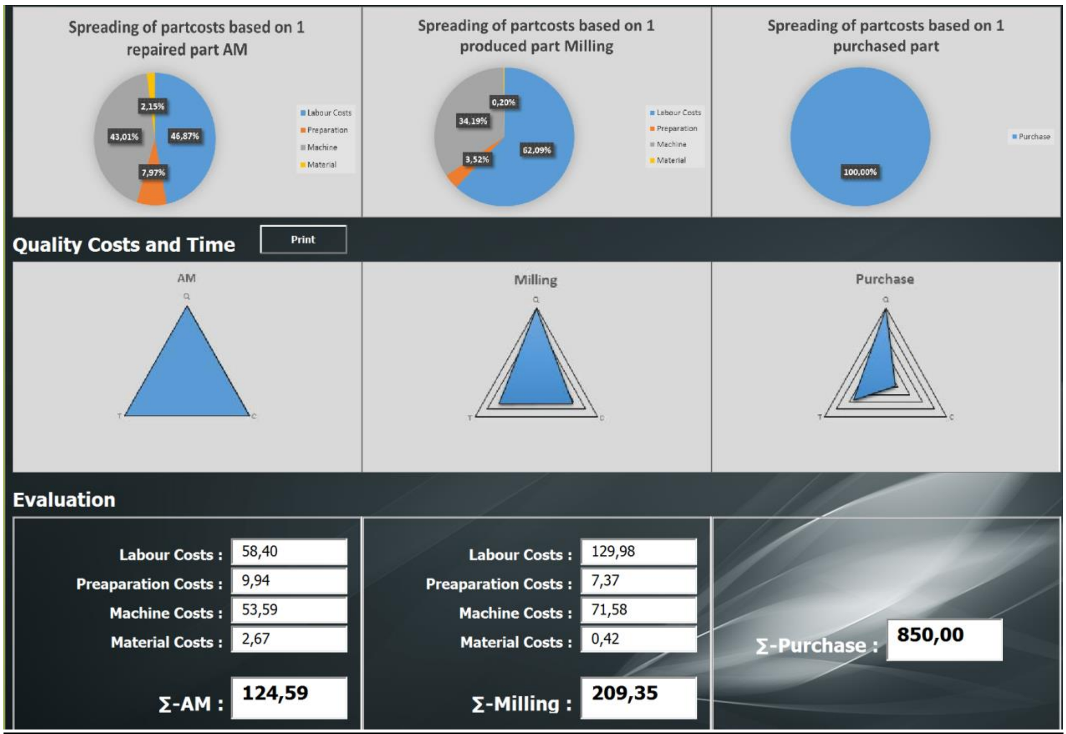

Figure 4: Evaluation of the calculation results

Another important aspect for aerospace is the documentation of this process to foster the transparency and the confirmability. Therefore a document has to be generated that contains all input from the operator and the databases and additionally all calculation results that the tool compiles in order to be able to reproduce the decision process. It furthermore supports the improvement of the tool as the output can be matched with data of the actual production process. This is especially relevant for AM as for example the build time estimation has to be enhanced.

Summary and outlook

Due to the specific characteristics of aerospace, Additive Manufacturing is suited to be applied in this industry. The required flexibility for low quantity and highly complex products cannot be realized by conventional technologies without reverting to extensive warehousing. The usefulness of applying AM for a certain use case yet has to be proofed. Therefore a methodology is required that supports the decision process. Especially because companies are not experienced in assessing the production costs of AM and additional benefits have to be taken into account to fully exploit the benefits AM offers. Based on identified key cost drivers four configuration units have been set up. They provide a standardized process to gather the data that is required for the calculation of the repair choices which is supported by predefined data but can always be adjusted manually. The tool then calculates the expected costs for AM and milling and the procurement of a new part from the OEM. The evaluation is illustrated by charts showing the share of each cost driver from the overall costs. Additionally, quality, costs and time graphs provide information of the key elements of MRO business showing the overall best solution for the defect part.

Thus, the concept for the decision component allows the monetary assessment of repair processes including AM. The documentation of the complete input and output data fosters the transparency and traceability of decisions which is a crucial aspect in aerospace.

For future work a detailed comparison of sample parts is required in order to assess the validity of the tool. Therefore the tool has to be improved in the evaluation of costs, quality and time to allow a detailed analysis of its functionality. It furthermore can be enhanced by strategic levels, calculating the product life cycle costs and an ecological investigation. The aerospace specific tool could also be adapted to the needs and specifics of other industries in order to proof its general applicability.

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