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# Integrating Additive Manufacturing in the Design of Aerospace Components

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Abstract. In the aerospace industry, Additive Manufacturing (AM) is quickly gaining ground. When optimizing the design of an AM component, all life-cycle aspects need to be considered. It is by no means limited to the classic weight / stiffness optimization of the topology alone. The AM component design must comply with an array of requirements on for example assembly, maintenance and inspection. In addition, there are the manufacturability requirements and constraints of the printing procedure itself, including component orientation and support structures. In this paper, a proposal on how to integrate the AM design of components with the design process is conducted, an interview study involving design and manufacturing experts has been made at an aerospace company, forming a base for the proposal. The result is that a primary design procedure for the AM component must be made as a separate step involving a limited set of design considerations prior to making a multidisciplinary evaluation of the proposed engine structure.

Keywords. Additive Manufacturing, Product Development, Decision support, Topology optimization, Aerospace

## Introduction

Lately, Additive Manufacturing (AM) has gained much momentum as a production process in a wide variety of applications [1]. Consequently, it has become increasingly important to design products for the AM process. Poor printability is perhaps to some extent acceptable when using AM as a prototyping method, but when manufacturing high end components where the importance of the part function and cost is paramount, much effort must be taken in designing for the process. This is referred to as design for additive manufacturing (DFAM).

One field of application where AM is quickly gaining ground is in aerospace. In aerospace applications weight reductions are very important. With AM, it is possible to manufacture topologically optimized structures giving important weight reductions. However, weight reduction cannot be the only consideration taken in design. The components need to fulfil a number of life-cycle requirements such as manufacturability, inspection and recycling. It is important to make all these considerations in an early stage of design, assuring that all requirements are met.

In this paper, it is discussed how to include the DFAM considerations in the design process of aerospace components. Introducing AM will perhaps also have other effects on the companies' offer to the customers, which is also discussed in the paper. To

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investigate these questions, an interview study involving four professionals has been made at an aerospace company. The objective of the interviews was to understand how the technology and product development is conducted at the company and how requirements are addressed throughout the process. It also involves finding out what tools that are used. Based on this, it is proposed how to integrate AM design in the context at the company.

## 1. Related literature

AM is not a single manufacturing process. It encompasses several different categories of techniques such as binder jetting, direct energy deposition and powder bed fusion. In the "ASTM F42 – Additive Manufacturing" standard, a categorization into seven categories are found. In each of these categories, there are several different AM techniques found. Examples include fused deposition modelling (FDM) and selective laser sintering (SLS). In this paper the selective laser melting (SLM) process is discussed. It is a powder bed fusion process where layers of metal powder are laid out and melted together by laser. When designing for the AM process, a number of general recommendations are found [2-4]. This concern geometric recommendations, how to orient the part in the printer, and how to build the support structures.

Often, an AM process is more expensive than a traditional manufacturing process, especially in larger series involving die-based processes. An added advantage is needed to motivate the extra cost. In [5] a study of an aerospace application is made showing that the cost of a part increased by a factor of 20 when changing from a forged to AM. Still, considering the high value of weight saving in the application, the change could be motivated. AM will in some cases also allow consolidation of many parts. The number of components in fuel injection nozzles could be reduced so that the number of welds and brazings went from 25 to just five [6].

Combined with topology optimization (TO), AM makes large reductions of the amount of material in a part possible because the intricate topologically optimized geometry can be manufactured [7-9]. Usually, TO involves minimizing the elastic energy under the constraint that the remaining volume fraction should be at a specified level. TO is generally done using finite element analysis (FEA) software, by applying different strategies for removing elements from the mesh until the solution containing least material is found [10]. The shapes produced in this way is a truss like structure that to a degree resembles trabeculae in bones (author's remark). This structure may from other life-cycle such as inspection or surface treatment be difficult or impossible to use as a component geometry. Modifications of the topologically optimized geometry are likely necessary to ensure compliance with all life-cycle requirements. In addition to stress and strain, other considerations can be included in the TO such as the residual stresses from the casting process [11].

To make the topologically optimized component useful in an actual aerospace application, all aspects such as aerodynamics, fatigue, thermal loads and assembly, inspection and manufacturability must be taken into account when designing. This is a very complex multi-disciplinary problem which currently cannot be represented in a single optimization. One strategy used is instead to generate a multitude of variants and analyze them from all aspects in a multidisciplinary manner [12, 13] and thereafter selecting a set of variants for further elaboration.

In addition, the requirements as expressed by customers can vary throughout the design process. An example from the automotive industry is found in [14]. An organization that can quickly respond to the fluctuations in requirements will have a competitive edge [15]. Therefore, increasing the company's ability to respond to fluctuating requirements should be addressed when the design process of a company is being formalized.

#### 2. An aerospace case

To find out how DFAM can be integrated in a design process, a study at an aerospace company has been carried out. Their current design process has been studied and a semi-structured qualitative interview has been conducted involving different professionals at the company. The studied organization employs about 2000 people and is part of a large global corporation. The company manufactures components for jet engines such as turbine frames, axles and fans. They have found that AM is useful for manufacturing components and have lately invested both in direct energy deposition and in powder bed fusion machines i.e. selective laser melting (SLM). This has created a need for the engineers to learn how to design components for the process.

The design process at the company is divided into two different stages, technology and product development.



Figure 1. Technology and product development.

Technology development is directed towards identifying future needs from customers and improving the current working procedures and manufacturing processes. It also involves developing and qualifying new conceptual designs resulting in a proof of concept, see Figure 1. The second process, called product development, is directed towards developing specific products in accordance with an agreement with a customer. In doing so the results from the technology development is used.

In technology development, conceptual designs are developed. As seen in Figure 1, technology development begins with the creation of a conceptual design. This is done in a creative manner involving several disciplines. A parametric CAD model of the conceptual engine design is created. To explore the concept and find out what the response on the engine performance from various aspects are when varying the design parameters, a multidisciplinary design exploration is carried out. This is done by making multi-objective analyses in a virtual environment. This environment consists of the CAD system in which many, geometrically different models are created automatically according to a design of experiment (DOE), varying 5-20 geometrical design parameters. This results in around 100 different variants that are sent to software that analyze them from several aspects such as aerodynamic, structural and thermal.

Manufacturability is also part of these analyses [13, 16]. In this way the design's response to variation is explored allowing informed decisions on how to set the parameters to best meet the customer expectations to be taken. These explorative studies are conducted in the early stages of technology development.

The results of the analyses are visualized graphically. This leads to a knowledge build-up on the behavior of the conceptual design. The whole process of analyzing the concept is automated using in-house developed scripts and software that are integrated via the application programmable interfaces (API) of the different software. Automation is necessary since there are in excess of hundred different variants to be analyzed from many different aspects. Steps have been taken to keep the time required to analyze each variant low, so that the whole process can be completed within a week or so.

When developing the product for the customer in the product development stage, the same environment is used. This time the variation is smaller since it was found roughly how to set the design parameters in the technology development phase. In the product development phase more fine tuning is done, increasing the precision of the analyses. The environment is also useful when requests for changes are made by customers. What-if analyses can be made quickly, increasing the ability of the company to react to fluctuating requirements.

# 3. Interview study

An interview study was made at the aerospace company to find the state of practice in the organization with focus on the technology and product development and how the requirements are handled. This was done as a preparation for introducing DFAM in the technology and product development. The interviews are part of a larger research project involving several companies and were conducted in May 2017. Of the around 30 questions, a subset of 20 questions were applicable to the scope of this paper. At the aerospace company, four different interviewees in senior positions were interviewed:

- 1. A technical lead engineer, responsible for the functions of technical systems, and requirements in manufacturing processes.
- 2. An engineer in thermal calculations.
- 3. A manager responsible for technical sales and preparation of quotations.
- 4. An engineer responsible for the product development for specific products after agreement with customers.

The interviews were made separately, and the duration of each interview was around one hour. The answers were voice recorded and then summarized in writing. In the sections 3.1-3.4 below, the answers from all four interviewees have been summarized. Some clarifications have been added by the authors. There were four categories of questions that were applicable in this study. Note that the actual interview encompassed several more categories:

- Technology development
- Product development
- Requirements
- Tools and systems

#### 3.1. Technology development

The R&T (Research and Technology) department works primarily with technology development. This is often carried out in cooperation with universities and research institutes. The drivers for this are mainly: (1) Addressing the need of new and improved products and (2) the necessity of bringing down the production cost. Addressing the first driver results in technology demonstrators that are run in test-rigs so that improvements in performance such as reduced weight, noise and fuel consumption can be demonstrated. The second driver leads to new manufacturing concepts. These need to pass a validation program, assessing their performance so they can be approved for use in actual manufacturing.

The company needs to have a close contact with current and prospect customers to perceive the future needs. One important channel is the product launches that are made by the aircraft manufacturers at aviation exhibitions. Unlike product launches in other businesses, there are in general no actual products ready at the time of the launch. Only preliminary designs and specification of envisioned aircraft are shown. This is done to indicate what type of aircraft that the manufacturer wants to have in the future product portfolio. After the launch, suppliers offer systems that they believe can fulfil the specification. However, in practice, unofficial contacts with potential sub-suppliers are taken beforehand. This is a way for the aircraft manufactures to get indications if it is feasible for the suppliers to design and manufacture the products that the manufacturers plan for the launch.

The customers are not directly involved in the details of the manufacturing at the supplier. They want a low price, but they seldom specify how the components should be manufactured if it fulfils their specifications.

In the company, it is the responsibility of the department "chief engineer's office" to first try to obtain beforehand information on the needs of the customer prior the product launch and then instruct the R&T department to develop conceptual products accordingly. It is also the chief engineer's office that prepares the quotation and the contract with the aircraft manufactures. The chief engineer's office also conducts the product development of the agreed product.

When making the quotation, the specific fuel consumption (SFC) is valuable information as well as the estimated cost and weight. In the quotation work, there are efforts made to minimize the cost.

There is competition among suppliers for the contracts. Therefore, some risk is taken when making an offer. There is perhaps not a complete proof of concept before it is offered. In such case, indications that it is possible to get the technology ready must be presented internally at the company before making the quotation. The expectation is to get the new technology validated as a part of product development after the contract has been signed.

When problems with products are discovered, root cause analyses are always performed. The results are documented in concept books, records and lessons learned at the end of each project. There are also reports from the design verifications available. This documentation makes it possible to understand how future products can be improved.

# 3.2. Product Development

There are several types of product development projects. It may involve developing a completely new product or reusing a successful product by scaling it for a smaller or bigger aircraft. These projects are extensive, with a duration of several years and require certification of the final product. There are also projects involving updates of existing products. They are carried out in a shorter time. Still, multidisciplinary calculations may be needed. If it can be proved that no form, fit or functions are affected then minor changes can be implemented within a few weeks to an existing product in product in production.

To some extent, existing products are offered to several aircraft manufacturers. However, there are always some minor differences between the variants. At least, the attachments and the software will be unique for each product.

The first priority in product development is getting a functioning engine. Simultaneously, efforts are made to reduce the weight and manufacturing cost. Function, weight and cost are addressed an iterative manner, where the refinement steps get smaller and smaller changes until the final design is reached.

## 3.3. Requirements management

The process concerning the requirements specification is central and is therefore carefully managed. The requirement specification that is applicable in product development is obtained from the customer. The requirement specifications are extensive documents specifying requirements for engine performance, service intervals and so on. It also specifies how to verify the compliance of the product with these requirements. From the requirements specifications obtained from the customer, an inhouse requirement specification is made that includes for example internal manufacturing process requirements. The requirement specification is also adapted to different disciplines such as market and engineering.

Some of the requirements are absolute as for example the certification requirements concerning strength and safety. It is in most cases the expected life time verses weight and cost that are negotiated with the customer. It is possible to make changes to the initial requirement specification provided that convincing arguments are presented.

There are no special tools for requirements handling (except word and excel). The customer relations management (CRM) is used for keeping track of some requirements such as when a customer requires a certain analysis to be performed in a certain way.

There is a variation in the requirements during the development process, especially those that are related to loads and interfaces. Lately, there have been some changes in requirements related to the environmental legislations such as the European union legislation for chemicals (REACH), stipulating the phasing out of certain materials and manufacturing processes.

## 3.4. Tools and systems

The company uses many different types of software for simulation. These are used as standalone applications for interactive use, or as part of automated routines to make design studies involving many variants. Both the chief's engineer's office and the R&T department uses the same IT-systems and tools. This creates a vast amount of

information that needs to be stored in an indexed way allowing rapid information retrieval. Work is ongoing to use the same product lifecycle management (PLM) system throughout. SharePoint is used for information sharing in the non-formalized part of the development work. The company is striving towards a uniform catalogue structure in all projects to facilitate information retrieval and sharing between projects. All information sharing between project are subject to prior assessment to avoid violation of confidentiality agreements.

The company uses design practices (DP) which are textual documents to convey a preferred way of conducting the development work. They specify for example when and what types of analysis that should be carried out and how the results should be interpreted. The DP:s make it easy to get an overview, but they lack detail so that it can be difficult to understand the details of the work from the DP:s. The sources of information in the product development process are web pages, both internal and external along with the product data management (PDM) system and databases for patents and materials. Some of the systems are not integrated. It would for example be useful with a connection between the materials database and the FEA system allowing for example material properties to be directly used when making FEA.

After each project, everything is documented in concept books, records and lessons learned. In addition, there are reports from the design verifications. This information is found in the PLM system.

#### 4. Introducing AM

To make an AM part successful, the amount of material in it must be minimized. A common way of accomplishing this is via TO. This cannot be directly integrated in the multidisciplinary design exploration environment in the technology development described in section 2. Making a complete multi-disciplinary optimization (MDO) involving TO is currently not feasible because of the required computing power and the practicalities in setting up the optimization. Further, formulating a single objective function weighing together the responses from all individual disciplines has proved to be difficult. Instead, it is proposed that AM design and evaluation is done in two steps involving first the component and then the engine assembly as shown in Figure 2.



Figure 2. Proposed inclusion of TO in the design exploration.

Starting from the left, a conceptual design has been made. The conceptual design includes an assembly of several engine components, not just the AM part. To analyze the AM component separately, the loads acting on the assembly must be localized to the AM part. As an example, a requirement on stiffness may have been specified on the

assembly. Prior to TO, the contribution of the AM part to the stiffness must be established. Other requirements such as geometric constraints related to DFAM will presumably also be possible to include in the TO. This can be realized by introducing a rule-base or likewise to direct the TO algorithm penalizing design that violate the manufacturing rules. The details of this is presently unknown to the authors. When the AM component design is completed, a parameterized CAD-model of it is made. It is put in the assembly context where a multidisciplinary design exploration is performed. There will presumably be some iterations needed including redesign and re-evaluation of the AM part before it can be shown to comply with all other requirements. If not, the TO step will need to be done over again.

# 4.1. Integrating AM in technology and product development

When doing modifications of existing engines components, it will not be possible to replace them with AM parts since it would require a new certification of the engine. Instead, AM parts will emerge in future engine concepts. The qualification of these products is still several years in the future. Currently, it is in the technology development phase that the efforts are made. There is an assumption that weight can be saved, but there should be an ongoing quest for added advantages of AM such as the consolidation of several parts into one. There are also sustainability issues that possibly can be addressed with AM. The organization can benefit from studying published case studies concerning design of AM aerospace parts.

The documentation of the performance of existing components both in service and manufacturing is a valuable source of information. It will be possible to identify problems that potentially can be solved using AM and to be considered when creating the new conceptual designs.

As for the ability to tackle fluctuating requirements, the effect of introducing AM parts is unpredictable. As with all manufacturing processes, designing for the process is important, so the actual designing will not be shorter or more agile. Rather the opposite since the design explorations will require a separate TO step for AM parts. There can possibly be a reduction of the time required to prepare for production because is faster to design support structures for printing compared to designing dies for a process like casting.

The way how the requirements set from the customer is complemented into company requirements has an influence on the design of AM parts. The AM process has a different set of requirements than traditional manufacturing. The requirements must therefore be scrutinized so that they do not make it impossible for AM to be introduced.

The AM part TO of Figure 2 can likely in many cases just not be based on the stiffness requirement and some DFAM considerations. One example is the aerodynamics of the parts located in the airflow through the engine. The topologically optimized structure considering only stiffness will have poor aerodynamics. A new algorithm that minimizes the weight under the constraint that the aerodynamical drag cannot exceed a certain value and the stiffness cannot fall short of a certain value is perhaps needed. Alternatively, removing as much material from the part as possible must be made by a human designer. Thereafter, the design proposal is evaluated.

## 5. Conclusions and future work

This paper has contributed to the understanding of the technology and product development processes in an aerospace company. The development of AM components is currently addressed in technology development. Product concepts involving AM parts will first arrive in the automated multi-disciplinary concepts exploration phase. It has been established that the component TO currently need to be treated as a separated step with a subset of design considerations. The reason it is that it currently not possible to address all multidisciplinary considerations in a single TO. In future work the details of which multidisciplinary considerations that can be brought into the TO step and the prioritization among them will be explored. This is planned to be done by studying the technology development process for actual topologically optimized components. Minimizing the number of iterations in the design exploration step should be a priority since it will reduce the time for making the analysis and thereby increasing the company's ability to respond to fluctuating requirements.

In the conceptual design phase, advantages in addition to the important mass reduction must be sought. An example is how AM can make it possible to consolidate several components into one. Identifying those additional objectives is highlighted as important when pursuing the research started in this paper.

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