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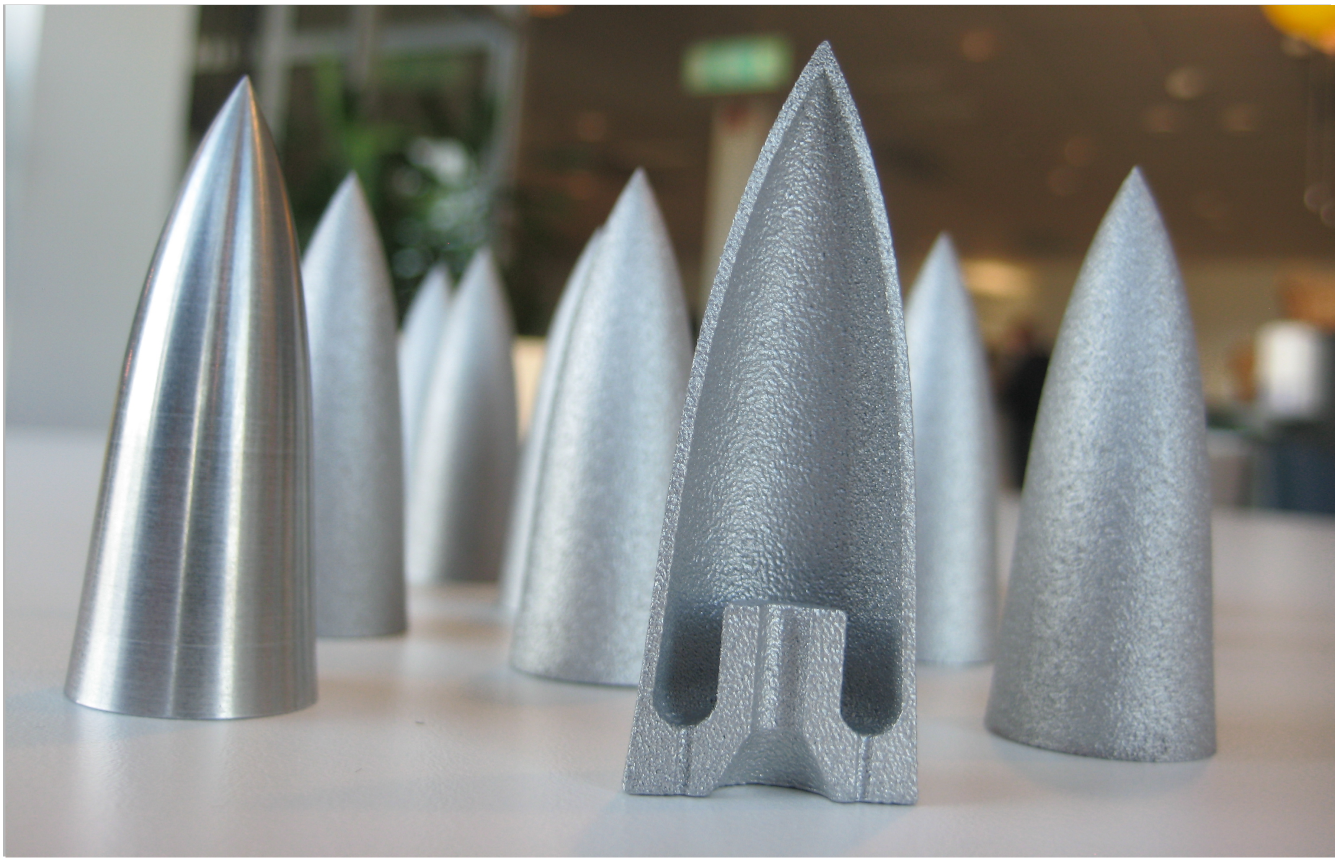

Evaluation and transformation for additive manufacturing (ETAM)

A Method for Conversion of High-technology Metal Products for Rapid Manufacturing

Master's thesis in Quality and Operations Management, and Production Engineering

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Department of Product and production development
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Gothenburg, Sweden 2015

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Cover:
A picture of the additive manufactured prototypes from the case study, among them a cross section of the product in the foreground and an after-treated prototype to the left. More information of the prototypes of the cast study can be seen on page 45.
Photographers for cover photo: Linn Hedström Kuosmonen & Pamelina Olsson

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Abstract

Additive manufacturing is a production method which is built on the principle of adding material when creating geometry, in contrast to many of the more traditional manufacturing methods that removes material. This method opens up for new possibilities for product design, and could potentially be a game-changer in terms of possibilities in production and product development. In the industry today, many companies are interested in exploring additive manufacturing, but often forgetting the importance of taking advantage of the possibilities as well as dealing with the limitations that the method also has.

The aim for the project was to map the possibilities and limitations with additive manufacturing (AM) of metals and also to investigate key factors for converting a high technology metal product for AM. To facilitate this research literature studies, interviews with key individuals and a case study in the form of a weight reduction of an antenna element was performed by the authors at SAAB EDS. The results from the project were presented as design recommendations for the antenna element and as a method for evaluation and transformation for additive manufacturing (ETAM).

The optimum design for the antenna element was a shell-like design with a wall thickness of 1 mm. An issue regarding the surface finish gave contradictive results and one only printed alternative was presented although it was showed that it was possible to use turning as an after-treatment method to increase the quality of the surface roughness.

ETAM is divided into two parts: evaluation for AM and transformations for AM. The first part contains analyses of strategies, technologies, supply chain and other aspects usually connected to the management and the second part is a straight forward way of investigating requirements and re-designing a product. The second part of ETAM is finalized when a final design is decided upon and a plan for manufacturing is made. ETAM is presented in detail in this report and a summary of the method is presented as a pamphlet.

Keywords: Additive manufacturing, rapid manufacturing, 3D-printing, operations management, product development, antenna element.

Acknowledgements

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Further we would like to thank all persons that have helped out with their expertise during the project. A special thanks to Daniel Lindbom at SAAB EDS for his patience and help with the simulations and Karolina Johansson at Lasertech for her advisory support within additive manufacturing.

Linn Hedström Kuosmonen
Pamelina Olsson

Gothenburg, November 2015

Abbreviations

3D – Three-dimensional

AM – Additive manufacturing

BOR – Body of revolution

CAD – Computer Aided Design

EBM – Electron beam melting

RM – Rapid manufacturing

RP – Rapid prototyping

RT – Rapid tooling

SAAB EDS – SAAB Electronic defense system

SBD – SAAB Dynamics

SLS – Selective laser sintering

SME – Small and medium-sized enterprises

STL –Stereolithography.

TQM – Total quality management

TTC – Tillverkningstekniskt centrum

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1. Introduction

For many organizations, among them SAAB Technologies AB (SAAB AB), continuous improvement and constantly striving for being better and more profitable is important. One way for high technology companies such as SAAB AB to decrease production cost or increase the performance of a product could be by producing with additive manufacturing (AM), commonly known as 3D printing. AM has been a popular research subject for decades (Goldberg, 2014) and has developed into three different areas of AM: rapid prototyping (RP), rapid tooling (RT) and rapid manufacturing (RM).

During the last decade AM has turned into being more applicable to metal manufacturing. Hilton and Jacobs (2000) identified the three main drivers of development in rapid manufacturing referring mostly to AM, and implementing this as a technology not only used for prototyping or tool manufacturing, but also for end-use product. The first driver is reducing time and cost of product development for new products. To keep up with changing needs of customers, and in order to stay relevant, a company could benefit from reducing the time between initiation of product development and market entry The second driver is reducing the manufacturing cycle time by making the process more effective and efficient, which also connects to this aspect. The third and last driver is reducing the cost of tooling which suggests increasing the capability of customizing for niche markets, and also enabling mass customization. By using AM in all three areas, RP, RT, and RM a faster quality production could be achieved.

SAAB EDS has an interest in evaluating how their high technology products can benefit from the AM technology. With high material specifications, complex geometries, tight tolerances and with focus on function, producing SAAB EDS's products with AM could be more beneficial than conventional manufacturing methods. Research has been done on general implementation strategies for AM as well as on some design features however there is a gap of knowledge as there is no method for product development focusing on work procedures that is widely accepted. There is a need of more experience of AM in the industry before AM can be seen as a natural contender among the conventional manufacturing methods for new product development. Many organizations like SAAB EDS are curious about AM and as a step in increasing their experience level a natural progression would be to start re-designing existing products for AM.

This report is a master thesis carried out during the 2015 at SAAB EDS. The aim of the thesis is to create a method for evaluating if AM is a suitable alternative and, if so, provide guidance throughout the product transformations process. The authors are students from Chalmers University of technology studying masters in production engineering, and quality and operations management.

1.1 Background

In recent years, SAAB AB has begun investigating how AM as a technology could give a competitive edge in the business of high technology products, and how the method could be integrated in SAAB AB's operations. As AM can be divided into three main areas, and SAAB

AB has familiarized themselves with one of these successfully (RP), the other categories are also considered to be interesting for SAAB AB. Plastic prototypes are already being produced for new product development, but the company has realized that other applications and materials could be applicable to their production. Metal is a relatively new material type that AM is able to handle. This, in combination with the fact that new machines have made producing end use products possible, had led to SAAB AB being interested in changing their production method for parts of their products to AM, or RM which is the term used for this *rapid manufacturing*. This project focuses on how AM will change the prerequisites for product development and design when it is used for producing end use products and parts ready to be put in an assembly. The project aims to give an insight into if and how a part which is normally produced using conventional methods can be adapted for AM.

Additive manufacturing is currently not as common for metals as for plastics. For metal manufacturing, AM is generally far from the most commonly used technique. If metal parts produced through AM can meet the high standards that are set for high technological products, this might soon become more common. This change is something that will most likely affect the entire organization both at SAAB AB, but also in general for all organizations starting to use this method. This means that not only will needed adaptions connected to product development and production development be included, but also supporting functions in the organization. As this is a subject that is relatively new, a project like this, exploring the role AM could play in further development could be of value for a specific company, the production industry as well as the academic community.

There are several frameworks for the evaluation and implementation of AM, which is, referred to in this master thesis report, however, none of these give a structured step-by-step method for the transformation of a metal product to fit the production process, AM. A standardized work procedure to follow could therefore be of value, both for SAAB AB as well as the industry at large.

1.1.1 Additive manufacturing

Additive manufacturing is the general name for methods where adding material, instead of the more traditional approach, subtracting material is used. AM has been around since the 1980s, but it is only in later years that the preconditions for the method has evolved through innovations within for example the materials that can be used. (Huang et al, 2013)

The possibilities of AM applications seem to be endless, as it enables new geometries for products as well as changing the way production flows and supply chains are handled. AM can also handle a number of different materials, and the most commonly used type is polymers, but ceramics, metals and composites are also used. AM in metal is one of the frontiers in production and allows for new possibilities. Much research has been done on the subject however there is still much more that need to be explored before AM is an established method of producing parts for the general market, for example like the more established production methods milling and molding.

1.1.2 Saab Technology AB

SAAB AB is a high-technology company that focuses on military aeronautics, naval, land, civil security and commercial aeronautics. The company was founded 1937 and is divided into six different operations: Aeronautics, Dynamics (SBD), Electronic Defense Systems (EDS), Security and Defense Solutions, Support and Services, and Combitech. SAAB AB's headquarter is based in Stockholm and the different operations are located on different sites around Sweden.

SAAB Electronic Defense Systems

The division of SAAB AB in Gothenburg mainly focuses on the EDS operation and consists of approximately 1100 employees. The EDS division has previously come in contact with the concept of AM, and has purchased a 3D printer that can produce plastic parts, for prototypes as well as visualization and testing of concepts. SAAB EDS has a production site in Gothenburg. At this site most of the assembling and all of the final assembling is performed. Only prototype component manufacturing is performed in-house, suppliers perform all other manufacturing.

TTC

The Örebro region in Sweden has an industrial tradition due to the large amount of manufacturing SME in the area. This has led to a broad knowledge base within manufacturing techniques. In order to make use of this knowledge and for the area to stay competitive collaboration between industry, municipality and academia has been arranged. This arrangement is called "Tillverkningstekniskt centrum" (TTC) and is located in Karlskoga, Sweden. The operations at TTC will mainly focus on AM and computer tomography. The operations are formed in such way that all parts benefit from the collaboration through learning and knowledge exchange. One of the industry representatives in the TTC collaboration has for a long been SBD and more recently SAAB EDS has joined the collaboration. Lasertech LSH AB (Lasertech) is also a part of the collaboration in the role of an AM manufacturer.

1.1.3 BOR-element

The most common antenna elements used today in military warfare are tapered slot elements, bunny-ear element and TEM-horn. All these three possess a 3D structure and thereby depend on rotation which makes it difficult to assemble and disassemble. SAAB AB has a patent for an element called body of revolution (BOR)-element (Holter, 2007). This new element has specified geometries in two dimensions but is rotation independent in a third and thereby also

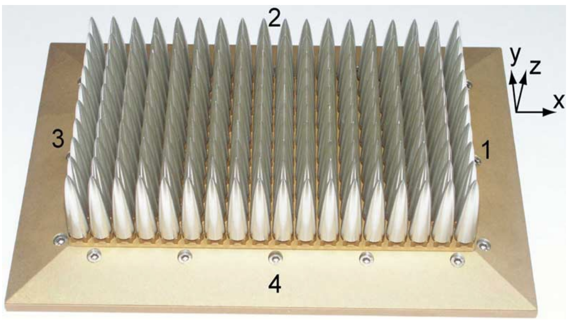


Figure 1 - Manufactured array mounted with BOR-elements in a rectangle for high frequencies. (Holter, 2007)

Figure 2 - High frequency BOR-element with an attached screw thread. (Holter, 2007)

easier to assemble.

The BOR-element exists in two sizes, one for high frequencies (6-18 GHz) and one for frequencies lower than that. It is used in an antenna unit for military purposes and can be positioned on a military boat, tracked vehicle or airplane. In a high performance antenna unit 200 elements are advisable. (Höök, 2015)

The antenna is designed in such way that the arrays collide with the BOR-elements and reflect between them (see figure 3). An electric signal is created in the surface of the BOR-element and is transported to the underlying structure below where it is analyzed. The reflection is one of the aspects that is important and depends on the surface finish. The BOR-element is manufactured through turning which gives a surface finish of 0.4 µm (See appendix A).

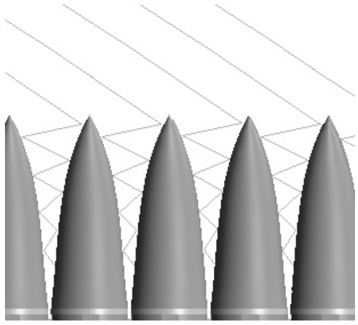


Figure 3 - Arrays reflecting between the elements.

1.2 Purpose

The purpose of the master thesis project is to create a method to aid in the conversion of an existing metal product from being produced by conventional manufacturing methods, to being adapted for an AM production, with focus on RM. The method will include key factors for decision-making both connected to specific product characteristics and to AM as a manufacture technique.

1.3 Delimitations

In this project the investigation of AM is limited to printing of metals. The AM area that is investigated is RM, while RT and RP will be excluded.

The focus of this project is on aspects in direct connection to product and production processes. This includes for example, the key factors connected to the ability of products produced through AM to meet the set product specifications, and what requirements there are on the production when adapting to AM as a method. Specifics regarding investments needed for an AM implementation, as well as specific managerial actions such as responsibilities and department belonging of each affected employee are excluded. The aspect of integrating part through AM is not considered in the creation of the method.

The master thesis includes a case study, and be limited to the specific product, which is the BOR-element, and the following specific requirements. Although there are two types of BOR-elements this case study has focused on the larger one for lower frequencies. The case is limited to the current situation at SAAB AB, and how well AM is suited for this situation and the collaboration with TTC. The abilities of the 3D printers at TTC will be a factor in the testing of the material properties of parts produced through AM, and the testing is limited to these facilities.

When developing a method for the implementation of AM, previous research and existing frameworks have influenced the outcome. The testing of this method was limited to the assigned case.

1.4 Problem analysis and research questions

AM for prototypes and tools has been used in industries for some time, but the usage of AM for the final product is something that has emerged in more recent years (Atzeni & Salmi, 2012). There is an increasing number of companies that are interested in finding alternatives for replacing conventional manufacturing methods with AM or more specifically, RM. The need of having processes that handles the work process of AM is increasing, and today, little research has been presented regarding everyday operations.

Changing a manufacturing method causes new possibilities yet new limitations for the product. These include the general benefits and drawbacks but also more specific factors regarding the product requirements, product development, production development and organizational issues. One large part of the implementation process of AM, especially for RM, is how to convert the product for the new manufacturing technique. This master thesis aims to identify how AM changes the standards set by conventional manufacturing techniques. Hence the first research question is:

RQ1: In what way does AM change the starting point for product development, and product re-design, in regards to possibilities and limitations?

In connection to this it is important to know in which direction to go when the starting point has been identified. Many key factors need to be investigated when converting a product for AM. The starting point is important, however all the way from the existing product to the AM produced product is interesting yet unexplored. With this as background the second research question is:

RQ2: What are the key factors to investigate when converting a product to additive manufacturing as a production method for high technology metal products?

By answering these two questions, a deeper understanding of the process of converting and transforming an existing product to an RM produced product will be given.

2. Method

This master thesis has followed a method that can be seen in figure 4. The early stages consist of a *literature study* and *interviews* in order to gain knowledge for the *method design* (later to be called ETAM) and also *calculations and simulations* in the early stages of the *case,* where the authors acted as project owners and coordinators. The research in the early stages was the basis of the key results of the project; therefore triangulation is a key aspect in increasing the credibility of the collected data, to give the project a solid foundation to work from (Bryman & Bell, 2011).

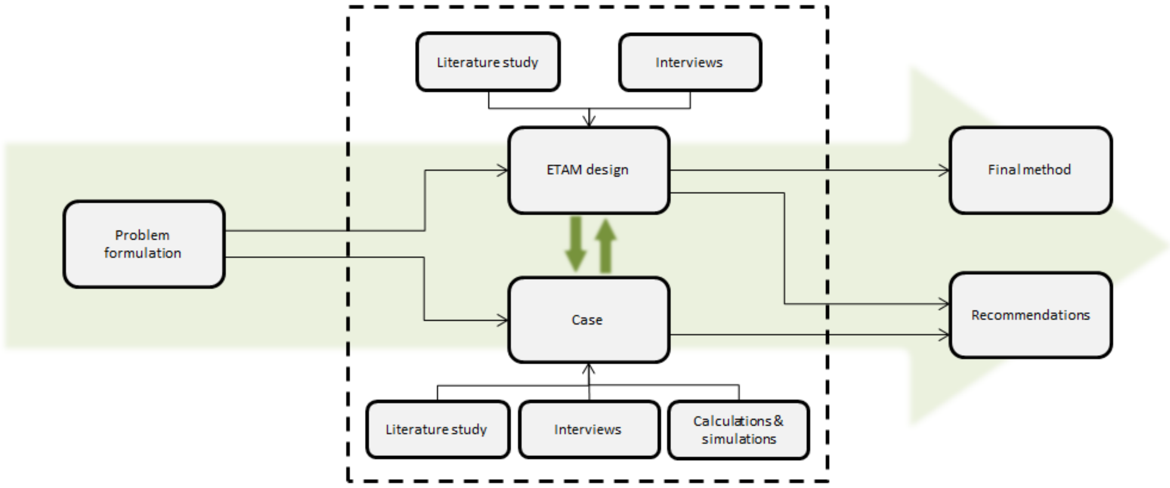


Figure 4 - Research method for the thesis project

A large portion of the project was devoted to *ETAM design* and to the *case*. This phase was an iterative process with parallel work with the method drafting and the case specific tasks. The case will influence the design of the method although findings from the method design will also affect the progress of the case study. The results from both parallel flows will end up in tests of both the *ETAM design* and the *case*. The results from the project will consist of a final method and recommendations regarding the case. All the steps of the method will be presented more in detail in the following chapters. Also the matter of ethics regarding this project will be evaluated.

2.1 Literature study

In order to gain background knowledge a literature study was conducted. The study was separated into three blocks concerning; general knowledge about AM, the method design and the case study. In the first block the major areas of concern was technical information of AM and material properties but also the history and future of AM. The second block involved data collection involving operations and quality management. The third block concerned studies of antenna theory and product specific information.

Mainly the Chalmers library, both the analog and the digital library, was used to find relevant literature. The digital library consists of databases with information from all over the world. Useful key words were: additive manufacturing, product development, production development, material properties, operations management, 3D printing and BOR-element.

Although the main part of the literature study was conducted in the beginning of the project additional theory was needed during the course of the project.

2.2 Interviews

To collect qualitative data, several interviews were conducted during the project in order to gain further understanding of the case and the method. The interviews were semi-structured meaning that questions on the relevant subjects were prepared in advance, in combination with an interview approach inviting a discussion around the subject rather than a straight answer. Non-prepared follow-up questions were asked during the progress of the interview. The prepared questions were sent to the interviewees in advance to the extent that was possible. With the permission of the interviewees the data collection was audio recorded. The records were transcribed and summarized.

In the beginning of the project initial interviews were held in order to gain knowledge about the product for the case. In a later state more specific interview were held in order to widen the knowledge base regarding AM and the theory behind the BOR-element. Interviews in order to fit the method into SAAB AB's working procedures were also conducted. Experts from different areas were asked questions about their expertise relevant to the product for the case. The interviewed people were the following in alphabetical order:

- Lars Emanuelsson – As a producibility expert at SAAB EDS Emanuelsson has a lot of experience regarding what aspects SAAB evaluates in a product development design process. Emanuelsson can also give an insight of what manufacturing costs to expect for the conventional manufacturing methods at SAAB.
- Farhad Golkar, Arcam AB – Golkar works at Arcam AB, one of the leading companies within AM in metals.
- Sebastian Hällgren, SAAB Dynamics (SBD) – Hällgren is a post-graduate at SBD. His work partly consists of evaluating SBD's products for AM.
- Anders Höök, SAAB EDS – Höök is an antenna specialist providing with both general antenna knowledge and specific information about the case study product.
- Karolina Johansson, Lasertech – Johansson possesses unique knowledge within AM and is one of few in Sweden working full-time with AM in industries. She has experience of manufacturing a large variation of products with AM. Lasertech is part of a collaboration (TTC) with SAAB EDS as one of the partners.
- Sofia Målberg, Sveriges tekniska forskninsinstitut (SP) – SP runs a project about AM involving many organizations in Sweden. Målberg is the manager for this project.
- Ronnie Petrini, SAAB EDS – At SAAB EDS Petrini works as a section manager at the mechanical engineering department and is well familiar with the development processes at SAAB.
- Joakim Ålhgård (previously Karlsson), SP – At SP Ålhgård is part of the AM project at SP run by Målberg. Ålhgård has a PhD within AM and specialized in the EBM method. (see theory for EBM)

2.3 Calculations & Simulations

In the product development project, carried out by the authors, calculations and simulations were conducted in collaboration with key individuals at SAAB EDS who have access to certain specific software, and have knowledge in the areas necessary for the function of the BOR-element. The specific details of this will be described both in chapter 3.2 and 5.1. The mechanical analyzes were conducted with support from Daniel Tidman-Lindbom, expert in structural topology optimization and solid mechanics.

The authors gave input to the key individuals that contributed in this step, and gave them instructions on what to investigate. The master thesis students also carried out a number of these calculations and simulations together with these selected key individuals.

2.4 ETAM design

The method for evaluation and transformation for additive manufacturing (ETAM) was mainly developed during creative sessions where findings from the literature studies and interviews were combined. The main purpose with these meeting was to find a structured process that was suitable and material to visualize this process was used.

ETAM was developed simultaneously as the case although the case also functioned as a test for the created method (See 2.5). Interviews with process experts at SAAB EDS were also held in order to validate the method (See chapter 2.2). The final design of ETAM was distributed at SAAB EDS as a step the implementation.

2.5 Case study

To facilitate the research a specific part among SAAB AB's products has been investigated, a BOR-element. The reason this product is interesting is the goal to decrease weight. The product was chosen since it is considered to have a scope wide enough to give insight to the required process of evaluation and possible re-design but it is still manageable within the given timeframe.

The case was conducted as a product development project at SAAB AB with needed experts involved lead by the authors. The project included an investigation of how well the ETAM method works in practice, as well as contributing to forming of ETAM through experiencing the process of adapting a product to AM, first-hand. As ETAM was being created and developed in parallel to the case study, much could be learned and added to the method as the project progressed. Tests and simulation has been conducted by the authors with assistance from experts or in some cases been leased out by the authors to experts when too much relevant knowledge was required. The results from the case became suggestions to SAAB AB regarding the future of the BOR-element and the findings from the development process contributed to the method (ETAM) that was created as well.

2.9 Ethics

SAAB AB is a company working within the security market with many countries' national defense as some of their customers. This means that much of the information that SAAB AB handles is classified, not only on a corporate level but also on a highly confidential level. The high level of security is a fact that needs to be considered during this project, both in terms of data storage and information in the final report. Confidential information in the report will be avoided to the greatest extent possible in order to decrease the need of censorship.

The security market that SAAB AB operates in can include customers within the military sector. Some of operations connected to this sector can be questioned in terms of ethics however the product in the case of this project is not aimed to cause any harm but provide the user with valuable information.

One of the major data collection sources in this project were be interviews. During these interviews it was important to inform the interviewees about the nature of the research in advance as well as why it is important as a research, but also what the interviewees gained from contributing. (Bryman & Bell, 2011) Since most of the interviewees were interviewed in the role of an expert it was preferable if they did not want to be anonymous, however they were be offered that possibility. To avoid data loss the interviews were be recorded with the interviewees given consent.

3. Frame of references

A large part of this project has been conducted through a literature study on related subjects. In this section the findings from this study are presented. The study has been divided into the following categories: Additive manufacturing, Performance testing and quality control, Quality improvement, Operations management, and Product and production development. Some interviews have contributed to this data collection and are part of this chapter. Complete summaries of the interviews can be seen in appendix B-J.

3.1 Additive manufacturing

Additive manufacturing (AM) is an upcoming manufacturing method that competes with the conventional ones. The definition of AM is as follows:

"The process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methods, such as traditional machining." (ASTM Standard, 2015).

This chapter will present the fundamentals of AM, this includes the history of AM, technical information, as well as opportunities and limitations in the process.

3.1.1 The beginning of Additive Manufacturing

Additive manufacturing is a method which is based on adding material, layer-by-layer to create shapes. The layers each correspond to a cross-sectional slice of the 3D model of the intended product that is to be produced. The concept that later would become the first type of AM was first introduced in 1981 by researcher Hideo Kodama of the Nagoya Municipal Industrial Research institute, and was based on the idea of exposing photopolymers to light in a controlled way to create structures (Goldberg, 2014). A breakthrough in AM happened only a few years later in 1984 when Charles Hull invented the method of stereolithography (STL), based on this concept, making AM a reality (Goldberg, 2014).

The background for the invention of STL is that there was a need at the time, in the industry, for being able to produce prototypes for production projects faster, easier and at a reduced cost. It was found that the prototyping methods that were available at the time, for production plastics, were both considered being time consuming and labor intensive, and not very effective (Hull, 1986). The use of AM has led to a cut in production time by a factor ten, in the first decade of its use alone (Kruth et al.,1998). AM as a production method has been refined over the decades that it has been used, and the main application is to this day creating prototypes. As time has passed inventions have added to the possibilities of AM, with new AM technologies and materials have become available. Additive manufacturing has become relatively common topic in science, academia as well as the industry, and even though prototype production is its main application, it is now also used for producing end-use parts AM can be considered to be a disruptive technology in many cases, and potentially it has the ability to change the way products are produced and distributed. (Horn & Harrysson, 2012)

3.1.2 The Basics of the AM process

According to Gibson et al. (2010) there are eight key steps in converting a 3D model created on a CAD/CAM system into a product as can be seen in figure 5. These eight steps have been referred to in many articles on the subject of AM by other well-established researchers. The steps Gibson et al. (2010) presents is made to be general for any AM process sequence, however, some formulations in the text is associated with specific methods of AM. The eight steps were created for AM with polymers but they are still relevant for AM with metals. Therefore this even more generalized version is presented as a translation of Gibson et al.'s work, as an interpretation made by the authors of this project.

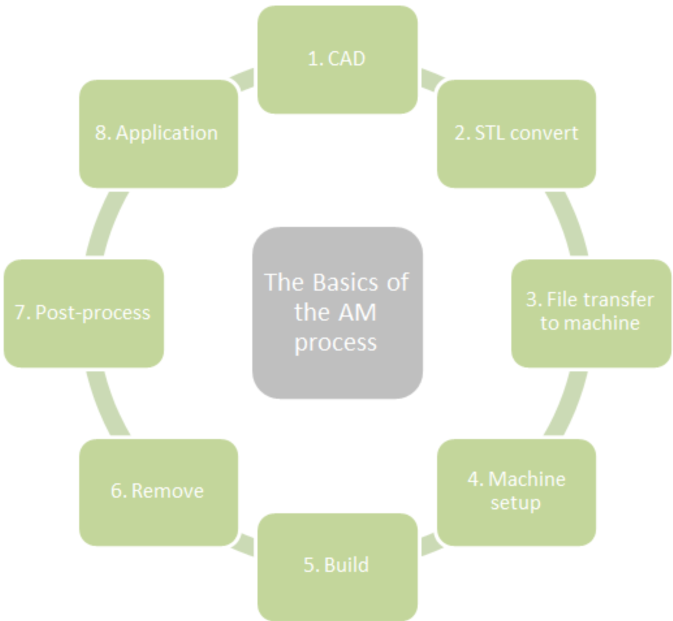


Figure 5 - The eight steps of the AM process described by Gibson et al. (2010).

Step 1 - Conceptualization and CAD

The concept needs to be evolved and the design prepared in a CAD program, where the focus is on the function of the product as well as the physical appearance. In the past a common problem with CAD models was that the surfaces that were created were not fully enclosed. The average user would possibly not detect this, and depending on what the CAD model was used for, would perhaps not have caused major problems or disrupted the other functions in the creation process of a product or part. However, when used for AM production, a surface that is not fully enclosed could create an unpredictable and unwanted outcome, as the AM machine would try and make up for the lack in design input from the CAD file. Different AM machines can apply different solutions for a problem with uncontrolled holes in the design, meaning that the output from one machine compared to the output from another could vary. Modern CAD software is created with this issue in mind meaning that there are checks build into the program that allows the user to see if there are any surface issues and gaps. Also when the CAD file is converted to a file format compatible with the intended AM machine, these problems connected to lack of enclosure areas are often detected.

Step 2 - Conversion to AM compatible file

AM machines need information which is based on the geometry of what is to be produced. The most common file format of this kind is called STL and is short for stereolithography. STL and other file formats of this kind which are compatible with AM provide the required information to an AM machine for it to be able to produce an intended part or product. The software generalizes the geometry of the intended product or part with a surface built by triangles that can be of different size depending on the setting that is chosen. This step involves setting an appropriate resolution, meaning the triangle tolerance, so that the triangles are not visible in the end-product. A low resolution will create an uneven surface, which will be represented, in the created part or product as can be seen in figure 6. However, if the resolution is too high the file will become unmanageably large, meaning that there is a trade-off between these two parameters. A rule of thumb that Gibson et al. (2010) describe is to choose a resolution where the offset of the triangles are smaller than the accuracy of the AM machine, but still close to the resolution of the AM machine.

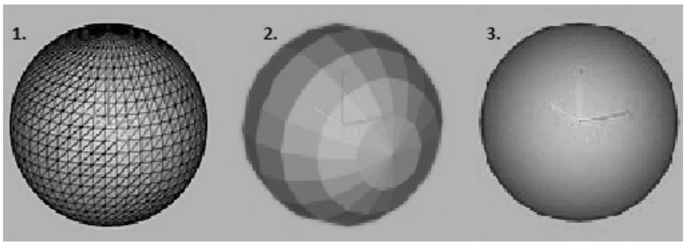


Figure 6 - 1) A globe created in CAD, visualizing the surface structure made up by a series of triangles. 2) An STL file translation with a low resolution, and large tolerances. 3) An STL file translation with a high resolution, and fine triangle tolerances (Basetech, 2015)

In this step there are possible issues, which were mentioned in the previous step as well, regarding gaps in the surface due to the generalization with triangles that have a tendency to not always be fully aligned, and creating gaps in the part surface. AM machines can for example automatically fill in these gaps with a default setting surface which may for instance not be of the same thickness as the rest of the part, which results in an unstable process. Gaps are more likely to occur when there are sharp edges in the design. This is one of the reasons why rounded surfaces are often preferred in design for AM. Also, to prevent this uncontrolled scenario it is important to correct and fill in gaps before the building process. Therefore there are built in tools to check for errors like this before the building process begins, in newer versions of CAD and AM machines.

Step 3 - Transfer and manipulate AM compatible file on AM machine

The converted file is transferred onto the computer controlling the AM machine. The part then needs to be checked to see if it is correct, and possibly reposition the part to optimize the printing process, as there are parameters to consider when it comes to the angle a part is printed in and how that affects the outcome. Often, more than one part is produced at the same time. This is also taken care of in this step, by adding more than one component or several of the same kind. A part may also need to be altered in size due to possible shrinkage for some applications, and also if there is after-treatment which demands this. Another possibility which Gibson et al. (2010) describe is labeling of parts which often can be done in this stage as parts may need to be distinguishable from one another. Modern AM software now also has the ability to give suggestions on possible sacrificial support structures that might be needed depending on the geometry of the part and how it is placed in the setup. (Gibson et al, 2010)

As Gibson et al. (2010) primarily focuses on polymers in the eight steps, and issues regarding overhang are more prominent in metal AM. This issue is not something that is mentioned in these eight steps of the AM process, nevertheless it is an important aspect to take into consideration, as it is something that can affect the outcome of the process in a significant way. Overhang is for example something that is often suggested to be avoided when designing for AM in metals. Mumtaz et al. (2011) mention how geometrical freedom is not in fact as free as often suggested, but actually limited partly by the issues that have to do with overhang. If a part can be rotated or shifted in this manipulation phase of the process, to make sure that for example overhangs can be eliminated, this could possibly increase the quality of the output as well as save time in later steps of the process. The aspect of AM limitations in regards to the produced output versus the desired output is discussed further in chapter 3.1.8, Limitations of AM in metal, below.

The software, which can suggest possible support structure that is needed in the machine setup before printing to secure a desired result, can instruct the operators in how to perform this next step. The support structure is removed after the building process is completed (Mumtaz et al., 2011).

Step 4 - Machine setup

Different AM machines can be better suited for different applications than others depending on the brand, and there are multiple setup options to choose from on AM machines that are available on the market. The setup of the machine will affect the end result drastically, making it important to choose the correct setup for that specific machine (Gibson et al., 2010). For example, some AM machines are able to process a larger number of different materials, or be able to change the layer thickness. Optimization can be needed to fit the specific product that is to be produced.

The parameters can be unlocked to change for example the layer thickness, meaning the thickness of the powder layer which is added for each single slice of the product. This is often at an additional cost from the machine supplier and with the loss off guarantee as a consequence, according to the expert (Johansson, 2015). Some AM machines will have the ability to speed up the printing process by enabling a compromise in layer thickness, which can in turn possibly endanger the process ability to fulfill the set requirements of the output (Gibson et al, 2010).

All free-standing or disconnected features of a part's geometry need to be kept in place by this support structure to ensure the quality of the produced part (Gibson et al, 2010). As there are two main systems for AM (see chapter 3.1.3) there are also different types of support structures that are used. The support structure may need to be prepared in this step.

Support structure is a necessary feature in AM design. As support structure increases the amount of needed material, as well as needed energy to both build and later remove, the use of it should be minimized. The amount of support structure needed can depend on the parts orientation, but also through the design of said part. (Calignano & Manfredi, 2014)

The reason that support structure is necessary is that it does have benefits that are vital for the AM process. One aspect that has already been mentioned is the problem with overhang, but there are other aspects as well. For example, support structure can help with raising the part from the platform in the AM machine to facilitate the removal of the part. It can also give extra strength to tall and thin parts as they are being built, as the process of distributing the metal powder in the powder bed can put forces on the part. Also support structure can lead away excess heat form the newly melted surfaces, which would otherwise cause distortion due to thermal stresses. (Hussein et al, 2013)

Step 5 - Build

In this step the layer-by-layer manufacturing process takes place. The computer controlling the AM machine will control this building step, meaning that this step involves much less manual work than the previous steps. The automated process involves layer control, height adjustment, material deposition, and layer formation. In this step there are different methods that are used and they will produce different results, and different AM machines will have different limitations, which are described by Yasa et al (2011) and will be described further in the chapter 3.1.8. Depending on what type of AM process is used the material will for example be added differently, which will affect the output of the process. The most common methods will be described further in the chapter 3.1.3.

Step 6 - Removal and Cleanup

In this step the building process is completed and the part or parts are removed from the machine. With most methods the part needs to be removed from the building plate, and when it comes to removal of excess material from the AM process. These support structures will be more or less difficult to remove depending on several factors. Distinguishing between support structure and part is a fundamental part of this step. Gibson et al. (2010) mentions how using a different material for the support structure than that of the part will make this process easier, as well as the physical removal of the excess material. Different material properties can be mechanical, visual or chemical. Mechanical means that the support structure can be weaker to make the removal easier. Visual means that the support structure is of a different color to make them more distinguishable from the material of the part. Chemical means that the support structure could be removed with a solvent that does not affect the part. This relates more to AM in plastics. For metals this could prove to be more difficult to apply in reality instead the same material design with a weaker structure is used. Also, Gibson el al. (2010) mention how fractures in the support structure can occur as a result of the AM process and how this can make the removal somewhat easier as well.

Step 7 - Post Processing

It is not uncommon that post processing is needed when using AM, and it is important to be aware of that. When the AM machine is finished the parts need to be removed from the plate it was built on. For metal parts, this can for example be done through using a wire EDM machine, where parts and additional support structure is removed from the machine. (Gibson et al, 2010).

The remaining support structure also needs to be removed from the parts, which can be done through several methods. Some level of surface damage will come as a result of removing the support structure. This process is made more manageable if the support structure is limited, and the surfaces they are attached to are easy to access with tools, etc. Surface roughness might also need to be improved through after treatments, to fit the different requirements on the part in question. It is not uncommon to use sand blasting to get a better surface finish after print (Johansson 2015). After-treatments should be chosen with the material properties in mind, like for example considering the materials heat resistance if the after treatment involved heat (Gibson et al, 2010).

Step 8 - Application

This step is mainly connected to the care and maintenance of the AM machines. As the process is relatively sensitive to outside influence, it would be preferred if the AM machines could be placed in a clean environment. Checks of the accuracy of the machines should be performed regularly to make sure that the process produces within the set limits. Also the handling of the material should be done with care to avoid contamination (Gibson et al, 2010).

3.1.3 Main types of AM processes

Generally, there are four main types of AM processes. These are powder-bed, powder feed, wire feed and another type which is only described as other processes, meaning that several differing methods are included. The first types of AM methods were the stereolithography, which was based on a layer-by-layer build, but the products were brittle and used for prototyping. The powder-bed method, which can be seen in figure 7, is the one that is the most accurate and enables the most flexible geometries to be built. The powder-bed method uses a building plate, often inside a controlled chamber, where powder of the intended material is put in a thin layer. The energy source, which for metals can be an electron beam or a laser beam, traces the intended pattern and melts the powder. After this process, a new layer of metal powder is deposited on top of the previous layer, and the melting process is repeated. (Brandl et al, 2011)

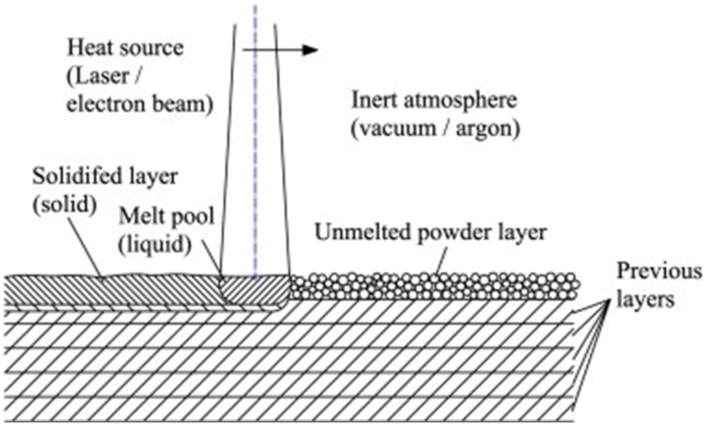


Figure 7 - Schematic drawing of powder-bed additive layer manufacturing (Brandl et al 2011).

Selective laser sintering (SLS) is one of the more common uses of powder-bed method. Also Electron Beam Melting (EBM) which is the method that the Swedish company Arcam created and holds the patent of, is a powder feed method (Arcam, 2015). Successful research within SLS has taken this method closer to selective laser melting (SLM) than SLS (Ålhgård, 2015).

3.1.4 Types of materials for AM

Materials that are used in traditional manufacturing technologies are not necessarily optimal when using AM. The first materials that were used in AM processes were in fact often brittle and for metals the structures created through AM were not as durable as its traditionally made counterparts. This was something that had limited the use of AM in the past, but is now changing for the better in AM processes. Materials that are optimized to be more durable, able to handle higher temperatures, as well as enabling a higher throughput rate than before, have been produced. This in combination with a higher resolution of the printed parts has made AM more useful. (Gibson et al, 2010)

Materials used for AM, especially for the powdered applications, can be mixed more freely than for traditional methods. There are examples of plastics being mixed with metals to create lighter parts according to Johansson (2015). Mixes of materials are not uncommon; however, machines parameters are often set to handle one type. This means that when changing material the settings on the machines need to be adapted. Different materials can behave in different ways; therefore the operator needs to be familiar with each material and process (Hällgren, 2015).

A single AM machine can be able to handle several different metal powders, which enables the user to change between materials. When changing between materials the process of cleaning the machine is an important step. For powdered AM machines this means cleaning out the powder of all remaining metal powder of one kind to be able to refill it with the new kind. (Johansson, 2015) If there are residues of the previous metal the new metal will to some degree be a mix of the two. If the metal powders are mixed, and the previous metal contaminates the parts that are created after a change, this can create uncertainty regarding the material properties of the part. The rate of contamination if the AM powder chamber has been vacuumed is low as the new material keeps the old powder down and as a result away from the product creation. (Johansson, 2015) However, it is an aspect that should be taken into consideration when discussing quality of the created parts. This type of contaminations can be detected by computed tomography (See chapter 3.2.4).

Common materials for AM in metals are as follows (EOS, 2015):

- Titanium
- Aluminum alloys
- A variety of steel
- Cobalt chrome
- Nickel alloys

Titanium is a relatively expensive material. Through traditional methods where there is a work piece that material is removed from to build the intended geometry, the level of material waste will be high. This leads to an increased total cost for the material use in production of titanium parts. (Målberg, 2015) Titanium is also a material that is hard to machine, but relatively easy to print, which is another reason why it is suitable for AM applications. It's possible to build strong low weight parts, using titanium. Another common AM material, Aluminum, on the other hand is easy to machine using traditional methods, and requires a slower building rate than titanium to produce quality products. Aluminum has a much higher electrical conductive ability than titanium, which has a very low conductivity level. (Hällgren, 2015) More data on the specific properties of the aluminum alloy used by EOS, AlSi10Mg, can be seen in appendix K.

Density of the AM parts can vary depending on the material that is used. While the titanium is 100 % in relative density, aluminum will achieve a slightly lower relative density. For example the EOS AlSi10Mg can achieve a relative density of 99,85 %. (See appendix K)

AlSi10Mg is a material typically used for casting, and has excellent properties for this method. (EOS, 2015) AlSi10Mg is also has good thermal properties which can be beneficial in AM because of the heat in the build; it has a low density but still a good strength and hardness as well.

3.1.7 New opportunities of AM

The main advantages of AM have been summarized and are described below. These advantages can be considered general for the AM technology; however, these may vary for the different specific methods.

Material efficiency

This is referring to the additive nature of the process, not removing unwanted material from a larger work piece but rather only producing what is needed for the intended design (Huang et al., (2013). One major benefit with AM as a production method is that the material that is needed for the process is close to that of the final product. The ratio between the required material for producing a product versus the material of the finished product is referred to, in the aerospace industry, as buy-to-fly ratio (Hotter, 2014) and as AM is known for providing a desirable buy-to-fly ratio, it an interesting method to investigate for producing parts for the aerospace industry.

When it comes to the AM methods using a powder bed, i.e. SLS, SLM and EBM, it is possible to reuse a large proportion of the powder that is used to fill the machine. This means that the process can recycle almost all material that goes into the process, except for that which has been turned into a part. (Gibson et al 2010) In cases where it is vital to ensure the purity of the powder this may not always be done, however, the possibility is there.

Weight reduction

In order to reduce the weight of components it is possible to hollow them out, as long as the function of the part allows it. This means that a topology optimization could be very beneficial when designing for AM, where the optimal design for the set boundary conditions can be created. (Gibson et al, 2010)

Resource efficiency

This is referring to the advantage of not needing for example fixtures and cutting tools. Also the added possibility of bringing the production closer to the intended customer can in many ways be a game changer. (Huang et al, 2013) An AM specialist Golkar (2015) at Arcam AB also mentions the possibility of having almost no down time due to tool changes as beneficial. The system can handle many different designs meaning that there is no need for tool changes between different products.

Part flexibility

Because AM often do not need to take constraints connected to tooling into consideration as traditional methods often do, the geometries can be much more free in their form. Also, the microstructure of the part can be designed in a much more free way, varying the mechanical properties of the material in the part. (Huang et al, 2013) Golkar (2015) defines the advantage of having no limitation in design of a part opens up possibilities to reduce the number of components in an assembly.

Production flexibility

The AM machines do not need as many set-ups as production can be synchronized, meaning that different parts can be produced in the same run in the machine. This allows for yet another degree of flexibility. (Huang et al, 2013)

3.1.8 New limitations of AM

As with all production methods there are limitations of AM. In a study by Yasa et al. (2011) a number of aspects of AM and available AM machines were evaluated, with a focus on powder-bed metal fusion processes. The parameters that were investigated were for example dimensional accuracy, surface quality, need of support structures, density, hardness and process limits like minimum wall thickness, overhang surfaces, inclinations and curvatures. These aspects, along with some other inputs are presented in this section.

Layer thickness and resolution

The layer thickness of the AM process is one factor that can limit what is possible to build. A rule of thumb is that most machines can build with layers of 0.1 mm at a time, though many use much finer layers than that. It is sometimes possible to vary the layer thickness by unlocking the parameter settings for the machine; however it may come at a cost. Making the layers thinner will give a more precise geometry than a thicker layer setting, however the tradeoff is that it will be a more time consuming process.

Regarding the resolution of the AM machine, there are limitations as to what can be built as well. For example one limiting factor is the area of the electron or laser beam. This means that it is not possible to build thinner or with higher resolution then the dimensions of the AM machine in question, even though it is possible to construct this in a CAD model. This will affect the dimensions that can be set for holes and curvatures in the design, and will play a role when scaling down parts. (Gibson et al, 2010) This is something that has been proven to be a problem, if not taken into consideration; therefore it is important to highlight (Emanuelsson, 2015).

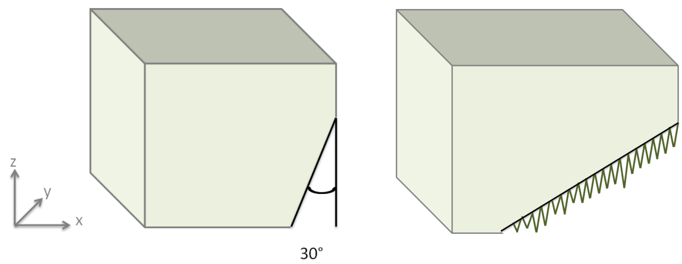


Figure 8 - The limit for overhang is 30º, larger angles than that will cause beard unless supported. The beard is illustrated to the right.

Geometrical and mechanical limitations

The size of what can be built in the currently used AM machines is limited. The largest machines do not produce as accurately as the smaller ones are not considered suitable for high-technology products; therefore they are not described in this report.

The geometry of the parts produced and their relation to the building platform will impact the quality of the surface. The surface facing downward in an overhang design is rougher than other parts, and is more likely to create a so called 'beard' which is a term used to by the experts such as Johansson (2015) as well Huang et al (2013) (see figure 8). The beard is formed when a structure is not attached to the underlying surface; excess heat is transferred down into layers in the powder bed below the intended layer, and solidified. This poses a problem for both overhang features as well as standing holes etc.

The surface roughness is also determined by the size of the grains of the powder in a powder bed AM machine. A finer powder will enable a finer surface roughness. This can for example be seen as a difference in EBM and SLS/SLM. Even though the resolution of the electron beam is less than that of the laser, the grains in the EBM machines are often bigger, meaning that products produced will have a rougher surface after the build. (Ålhgård, 2015) The hardness of the parts will depend on the method as well, along with the other mechanical properties.

The need for support structure is something that is a vital aspect to take into consideration when using AM in metals. Even though the support structure enables better quality the support structure should be kept to a minimum if weight reduction is wanted. Also, if support structure should be removed after the printing process, it is necessary to keep in mind that it should to be easy to access if it should be removed and that the removal is an extra step in the manufacturing process. The parts produced will also need to be removed from the AM machine after the build. This can be done through several different methods, but it needs to be taken into consideration and will affect the final product.

Imperfections and Cost

Imperfections can occur due to many different reasons, and to find imperfections can be somewhat difficult if the geometries of the parts produced by AM are complex and can include inaccessible areas (Målberg, 2015). This can require new methods of analyzing the produced parts such as computed tomography (see chapter 3.2.4).

The cost of using AM can be higher than other production methods, and sometimes be slower to use for simpler geometries. For example when it comes to aluminum it is inexpensive and easy to machine and is therefore seldom a good alternative for products that possesses a noncomplex geometry that turning or milling can handle. That is why it is so important to take advantage of the positive aspects of AM in order to make it a competitive production alternative. The production time, especially for larger and solid products, is much longer than for turning a solid rather simple geometry.

One aspect that can bring up the cost of using AM is the need for shielding gas in some applications. The process of AM of metals will in most cases take place inside a chamber of the AM machine providing a controlled environment, often using protective inert gas. The different AM processes will demand different inputs in the form of, for example, protective gas like argon, which will prevent oxidization and burning despite the high-energy concentration, and create better overall conditions for the process. (Air Products, 2015) The powder bed method SLS needs shielding gas, however EBM uses vacuum to prevent scattering of the electronic beam (Ålhgård, 2015).

The purity of the protective gas will have an effect on the output as well, since impurities can contaminate the parts as they are being built. There are companies specializing in helping AM production users to find the optimal gas for their process, which can be especially important when looking at high technological products and aerospace applications. Having a correct flow rate of the shielding gas and purity level of the gas in AM production will decrease the risk of getting oxidized parts with a high porosity. (Air Products, 2015) The need for optimization of the shielding gas, as well as not being able to use some of these production methods without it, without for example lowering the quality significantly can be seen as a limitation.

Another imperfection that is inherited in AM is that due to the build direction, the products will have certain anisotropy. As for example the SLS/SLM process consists of an extremely rapid melting and re-solidification, which affects the microstructure of the material. The products produced trough SLS/SLM can be after-treated with a heat treatment to reduce the inner stresses and anisotropy. (EOS, 2015) However, this does require an extra step in the process which will be of an extra cost as well as making the production time longer.

3.1.9 The future of AM

Researchers have been working on improving AM processes to overcome the abovementioned drawbacks. Nonetheless, it is unlikely that AM technology will make traditional manufacturing processes obsolete, which is something that the experts that were contacted in connection to this master thesis agree on. Even though AM could be a disruptive technology, which has the potential to change much of the industry not all experts agree that the method will revolutionize the industry. Målberg (2015) say that AM has many advantages, however, it is not Målberg's opinion that AM will be used in all applications, but rather be a production method among the traditional methods.

According to the AM specialist Golkar (2015), the AM technique has a number of different advantages that will increase in the future. These include increased productivity, larger components can be built, post-machining process not needed for surface finish, and more customized microstructure in components, as well as increase in beam powder, as the technique evolves. These advantages suggest that AM will become even better and usable in the future, according to the expert.

For implementing AM companies that have a background in rapid prototyping (RP) could have a possible advantage, as the method expands into more industries. With more experience and knowledge in prototyping will allow companies to make the transition from prototyping to the RM stage easier and faster.

The main a sector in which AM in metals is used today are the medical and aerospace sector. Golkar (2015) predicts that AM as a production method is going to expand in is mainly these two sectors. Then in the more distant future, AM could possibly expand more in both the automobile sector as well as being used to a larger extent for tooling.

There are also aspects that could be disadvantages for AM as a production method; Golkar (2015) identifies a few of these. There is for example the issue that the AM method is still a too advanced technology to replace existing technologies (such as casting) for production. There might also be a reluctance to accept this new technique, as it is not traditionally used in the industry. There could also be new material alloys with higher demands than the technology can handle. Today the technique is limited to pre alloyed powders, in powder bed methods. Also, introducing more materials that are not possible to use with the techniques that are available today, to use in the build. Another possible limitation for AM in the future, specifically for EBM, is that there may be difficulties which need to be solved in regards to controlling the electron spot will be more difficult with increasing beam power.

In the more distant future, Golkar (2015) adds that it is possible that the parts produced by AM will be even more customized then today. Golkar also predicts that the focus will not only be on production but also repair of metal components using AM.

3.2 Performance testing and quality control

When designing a part it is of great importance to conduct simulations and experiments in order to verify its performance. It is also essential to verify the quality of the produced product. Here follows a description of some tools that may be of use when performing this kind of testing, both in terms of mechanical and electrical properties.

3.2.1 Finite element method

A common method to use when analyzing a mechanic part or system is to use the finite element method (FEM). FEM has the ability to solve problems that are difficult to solve analytically and finds an approximated solution of the distribution of field variables in the problem domain. The method is built on dividing the domain into small geometries, so called elements, in order to analyze them separately. When analyzing the domain physical laws and principles are added to each element and the changed conditions for each element are measured. (Quek & Liu, 2014) By using this method it is possible to add constraints such as torque forces, tensile forces etc. and thereby simulate realistic scenarios that may occur.

Mechanical properties

Depending on how well an object can handle external and internal forces the mechanical properties vary. The forces can for example be pushing, pulling or rotating and depending on the size and direction of the force the affected object will respond in different ways. (Hen-Geul et al, 2009)

The tensile strength indicates how large external forces a part can stand. For example the forces or torque caused by assembling will build up tensions in the material. How much tensile strength a part has depends on the geometry of the part but also the material. When measuring the tensile strength the geometry is divided into different parts depending on how affected the area is. The most critical areas are often symbolized with the color red and the least affected areas are then colored blue.

Eigenfrequency

An eigenfrequency is defined as any of the natural resonant frequencies of a system The eigenfrequency of an object will determine how it is affected by vibrations. If the outside environment makes the object subject to vibrations that are in the range of the eigenfrequency there will be resonance in the object, and the object will begin to oscillate if there are no damping forces. To avoid this effect, it is preferred to design for an eigenfrequency that is not in the range of what is to be expected of the outside environment that the object in question would encounter. This can be achieved by designing for high eigenfrequencies. The eigenfrequency is determined by the design of the part, and will naturally be higher if an object is light. (Benenson, 2001) The result of an eigenfrequency simulation is a number of frequencies of varying size due to the modes of oscillation in the part. The lower frequencies are more common and are also causing the larger deformation than the object's higher eigenfrequencies. The test object should therefore be designed with the lowest eigenfrequency as a limiting factor.

3.2.2 Structural topology optimization

Structural topology optimization (STO) is a way of optimizing geometries. There are two subfields of STO that are used for different situations. The first optimization type is called *layout optimization* and is used to optimize grid-like structures. The topology gives suggestions on how to optimize a grid of suitable pattern and size. The second one is called *generalized shape optimization*, which is a way of deciding internal boundaries. By assigning a material to the inner volume a kind of material optimization can be done. Hollowness can be simulated if this material is assigned as air but other materials can be chosen as well. The boundary conditions can be connected to the materials, specific cross sections, external geometries etc. (Lewinsky & Rozvany, 2014)

3.2.3 Skin depth and the Huray model

In theory it is possible to manufacture conductors through AM since for example aluminum has high conductivity and can easily transport currents. If AC current runs through a cylindrical geometry it is possible that eddy currents appear. These eddy currents are shown in figure 9 and are circular currents in the conductor. By having these eddy currents the current in the center of the conductor are canceled due to the currents running in opposite directions, this results in a steady current on the outer parts of the conductor. This allows parts to be hollow since the function is only in the skin of the part. Also shown in figure 9 is the area of the steady current is dimensioned by the skin depth, which is the distance from the surface and how far into the conductor the current flows. (Hurley & Wölfle, 2013)

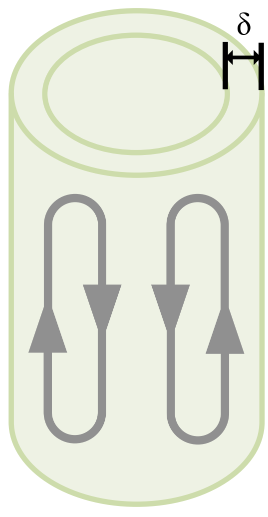


Figure 9 – Circular currents (eddy currents) within the conductor and skin depth δ.

The skin depth can be calculated as equation 1, where f is frequency, σ is conductivity and μ is the permeability (Hurley & Wölfle, 2013). This number gives an indication of how much of the outer surface that is used for current transportation. However, with a Huray model it is possible to analyze whether or not the surface roughness is larger than the skin depth.

Equation 1 - Skin depth

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$$

As the abilities of computers are increasing, the data rate that can be fed into simulation software is becoming even greater (Hall et al, 2007). Traditional models and approximations for simulating the effects of surface roughness on transmission lines on the integrity of the signal that is sent, like 1 and two in figure 10, were found insufficient. In the light of this, the Huray's model was created, which is a Multigigahertz Causal Transmission Line Modeling Methodology Using 3D Hemispherical Surface Roughness Approach. This model provides a fundamental description of conductor loss as determined directly from Maxwell's field equations (Griesi, 2014). The Huray surface roughness model can be implemented on copper foil layers, created through electrodeposition, which is commonly used in high speed circuits. A snowball-like modeling of the surface corresponds to actual scans of real copper surfaces; hence the model is also referred to as the "Snowball" model (Huray et al 2007). A simplification, in the form of a cross section of how the original hemispherical model looks compared to the multi-level hemispherical model described in the article by Hall et. al (2007) can be seen as picture 3 in figure 10.

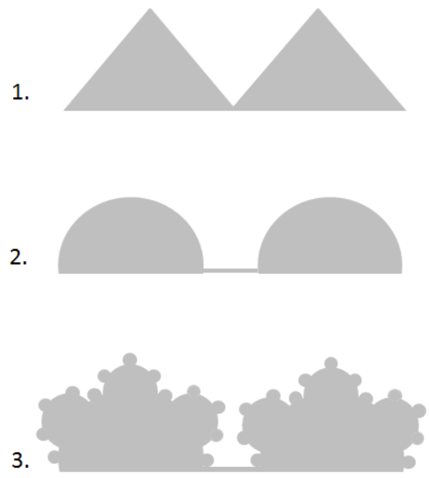


Figure 10 - Three types of surface approximations. The third one is a cross section of the "snowball" model by Huray.

3.2.4 Industrial computed tomography

Industrial computed tomography (ICT) is a technology that uses radiation sources in order to convert three-dimensional geometries into two-dimensional images in grayscale (Bin et al, 2007). The technique is useful for materials with high atom number, e.g. aluminum, titanium and copper. ICT is used normally to detect flaws and conduct particle analysis in materials without destroying the product. Voids and cracks can easily be detected without taking the product apart. Both internal and external geometries can be analyzed and the technology is therefore suitable for products with non-accessible internal features, such as components produced by AM. (De Chiffe et al, 2014)

3.2.5 Pugh matrix analysis

A Pugh matrix analysis (PMA) can be used as a method for sorting among alternatives during an improvement process. In a product development process it is possible to use this method in order to sort among concepts. The method consists of steps with deciding important criteria, weighing the importance of the criteria, setting a baseline for comparison, comparing the concepts to the baseline and finally computing the final scores for the concepts. The concept with the highest score can then be seen as the strongest candidate. (Cervone, 2009)

3.3 Quality improvement

In order to be successful over time all organizations must strive for continuous change and improvement. It is important to keep up with a changing environment and there is always room for improvement to avoid that the competitiveness decreases. As Bergman and Klefsjö (2010) states: "The value of continuous improvement is also a mental picture that everything can be done better that we are doing today, better in the sense that is provides 'better customer benefit' and better in the sense of expending 'with fewer resources'". (Bergman & Klefsjö, 2010, p. 45)

However, change is needed in order to have the possibility to improve. Driving through successful change is hard and although few changes turn out to be disasters very few can be considered successful as well (Kotter & Schlesinger, 1979). This section presents some knowledge about quality and change with a focus on implementing AM.

3.3.1 Total Quality Management

Quality and total quality management (TQM) has become commonly used words in many organizations of different kinds. Although many organizations claim to work according to TQM it is not too seldom the organizations are only using some quality tools and have failed in implementing a culture of TQM and fundamentally change the processes (Evans, 2005). There are many definitions of TQM, Bergman and Klefsjö (2010) define it as below.

TQM: A constant endeavor to fulfill and preferably exceed, customer needs and expectations at the lowest cost, by continuous improvement work, to which all involved are committed, focusing on the process in the organization. (Bergman & Klefsjö, 2010, p. 37)

TQM is based upon six cornerstones that are interrelated to each other (figure 11); committed leadership, focus on customers, base decisions on facts, focus on processes, improve continuously, and let everybody be committed. All improvement work should be based upon these cornerstones and supportive tools and methodologies. (Bergman & Klefsjö, 2010)

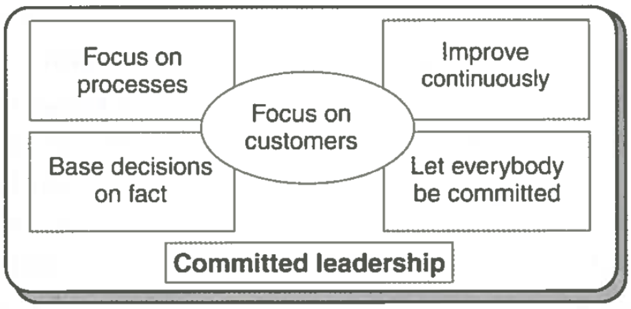


Figure 11 - The Cornerstone model according to Bergman & Klefsjö (2010, p 38).

Focus on customers

In TQM it is important to focus on the customer, it is the foundation of the whole quality philosophy. This usually refers to the customers' wants and needs. The concept of focusing on the customers mean that it is essential to find out what the customers want and need, even though the customers themselves might not know, and systematically striving for fulfilling these requests and expectations with the product. (Bergman & Klefsjö, 2010) The customer satisfaction is commonly depending on receiving the right quality in the right quantity at the right time and right place for the right price (Mukherjee, 2006).

Base decisions on facts

In order to fulfill the customers' expectations investigations are needed to ensure what it is that the customers really want and need, but also how much the customer is willing to pay for it. This is the main guideline for decision-making and speaks for not letting random factors be of decisive importance. This cornerstone requires analytical tools and methodologies for gathering, structuring, analyzing and deciding upon the needed information. (Bergman & Klefsjö, 2010) The necessary information involves customer satisfaction, product performance, market assessments, competition comparison, supplier performance, employee performance, and cost and financial performance (Evans, 2005).

Focus on processes
TQM is a lot about standardization and figuring out the optimal procedure for each activity. All activities in an organization are connected as processes, the trick is to control them and making them efficient. Sandholm (2010) describes processes as below.

Processes - a limited number of coordinated activities which together have a definite purpose" (Sandholm, 2010, p.85)

The aim with the processes are transforming the customer needs into a product that is providing the customer with the very same. Three common categorize for processes are: main processes (e.g. product development, production and distribution), support processes (e.g. recruitment, maintenance, information) and management processes (decision making, improvement implementation, planning). (Bergman & Klefsjö, 2010) The processes can be of varying size and aim for includes internal customers or both internal and external ones. A process can be continuous, cyclical or periodical and by controlling them the output can be evaluated and forming the optimal activities. (Sandholm, 2010)

Improve continuously
Having standardized procedures and processes is not enough. Even though they may be good they can always be better, especially when the environment and the customers may change over time. One can always reach better quality using fewer resources and therefore one should never be satisfied. (Bergman & Klefsjö, 2010) The improvements include for example the product itself, the work processes (in terms of waste, errors and defects), flexibility, responsiveness and cycle-time, and organizational management processes through learning (Evans, 2005).

Let everybody be committed
The success level of a company is directly related to the skills, knowledge and motivation of the employees. With highly motivated employees who are satisfied with their work situation the risk of losing competent workers decreases. (Evans, 2005) Thereby the possibility to increase the overall in-house knowledge instead of teaching new recruits emerges. To reach successful quality improvements committed and actively participating employees are key aspects and managers should focus on effective communication, delegation and training (Bergman & Klefsjö, 2010).

The possible managerial actions for encouraging commitment are many. Two of the most important ones are the distribution of information and teamwork. Lack of information leads to a less feeling of responsibility whilst a good information resource will cause a higher feeling of responsibility. (Carlzon, 1987) Teamwork eases good communication and can exists in three forms in an organization: *vertical teamwork* between top management and lower-level employees, *horizontal teamwork* such as cross-functional teams, and *inter-organizational teamwork* including relation and partnerships with suppliers and customers. Vertical teamwork is very efficient while improving quality. The person who is closest to the problem is probably the person with most knowledge about it and may be of great use while solving the problem on a managerial level. For this to work it is essential that all employees have knowledge about quality work. Horizontal teamwork is great for solving problems. People with different background, knowledge and expertise are likely to solve more complex matters together. A good inter-organizational teamwork with ones suppliers is important in order to quality assure specifications and have an efficient performance feedback discussion. (Evans, 2005)

The commitment for quality improvements does not only apply for in-house personnel but also to suppliers (Bergman & Klefsjö, 2010). This is one reason for why a close and steady relation to one's suppliers is important.

Committed leadership
To summon a group toward a common goal good leadership is necessary. When it comes to organizational leadership it cannot be emphasized enough the value of devoted and engaged leaders. Leaders that are committed to the group's task are needed on all levels of the organization and support in forms of management resources, company visions and financial resources. (Bergman & Klefsjö, 2010) This commitment to achieve TQM involves both long-term thinking. Even though the TQM strategies may be contrary to other strategies and it is important to have managers willing to make both long-term and short-term, more urgent, decisions following the way of TQM. (Evans, 2005)

3.3.2 Change frameworks for additive manufacturing
There are not many change frameworks for AM however some exists. Mellor et al. (2013) and Achillas et al. (2014) both presented strategic frameworks for AM. Both articles handle similar key investigation categories however Achillas et al. (2014) presents a process while Mellor et al. (2013) does not include a specific order. According to Achillas et al. (2014) the key steps are:

1. Determination of critical SKUs
2. Determination of alternative processes
3. Selected criteria and Inputs & outputs (two different but simultaneous steps)
4. Decision support system

Mellor et al. (2013) categorize them as: *external forces, AM strategy, AM technology, AM supply chain, systems of operations and organizational change*. Below follows an explanation of the categories.

- *External forces*
  An organization is dependent on both internal and external factors. A successful strategy is seldom successful if it does not consider aspects from the outside that can rarely be controlled from the inside. The external factors can for example be the competitive pressure, environmental legislations and customer requirements.

- *AM strategy*
  Having a strategy for future opportunities and obstacles is important. An organization can have several strategies such as, business strategy, manufacturing strategy, and research and development strategy. It is important that all these strategies are connected to each other and most importantly do not contradict each other. The

decisions regarding implementation of AM and the strategy for it affect many other strategies within the organization and must therefore be taken into account when forming several strategies.

- *AM technology*
  Before implementing a new production technique new knowledge about the method is needed. This also applies for AM. It is important to for example answering questions such as: What are the AM standards? How mature is the technology? What are the general benefit and trade-offs?

- *The AM supply chain*
  A new production method affects not only the organizations itself but its customers and suppliers as well. The location of the manufacturing site needs to be considered. One needs to consider how a change of site location can affect the distance to the suppliers and the customers.

  Another important aspect within this category is also the vendors of AM systems and what they have to offer. There can be a difference between what the research about the technology says and what the vendors actually offer. This also includes the material supplier, its location and its offerings in terms of amount, different materials etc.

- *Systems of operations*
  With new methods come changes in the daily operations. As previously mentioned (see chapter 3.1.7) the AM technology opens up a new geometrical freedom that off course brings along a need for changes of the designing processes. Also the quality control operations may need an update. The accounting systems for predicting the costs of AM may need an update as well due to this new method with new aspects to consider. The new operations connected to AM must be integrated in the ongoing daily work overall.

- *Organizational change*
  Change and improvement is connected to each other. Driving through change is seldom easy and can quickly involve many parts of the organization. How extensive the change work needs to be depends on the size of the change but also on the size of the business and the organizational structure. Added to this is the company culture. An important aspect here is how used the involved employees are to change and how resistant they might be. The experience and skills of the workforce is also an aspect that needs to be taken into consideration. All this determines how the change work is going to be lead.

Conner et al (2014) presents a three-axis model of deciding whether or not a specific product is suitable for AM or not. The suitability for a product can be decided depending on three variables: customizations, product volume, and complexity (see figure 12).

Through this model it is possible to divide products into eight regions: mass manufacturing (1), manufacturing of the few (2), complexity advantage (3), mass complexity (4), customized for the individuals (5), mass customizations (6) artisan products (7), and complete manufacturing freedom (8). (Conner et al, 2014) For these regions AM may be more or less suitable although it is also depending on the type of AM, i. e. RP, RT, and RM.

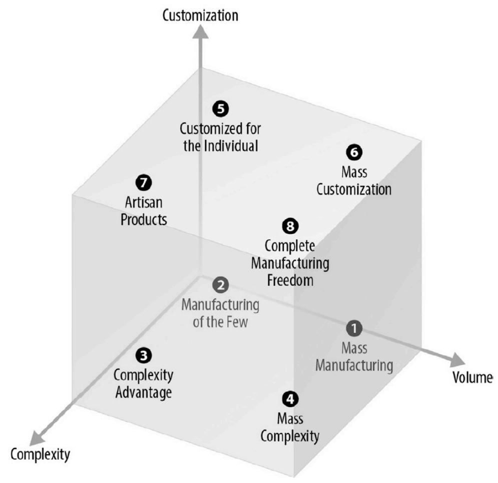


Figure 12 - The three-axis model presented by Conner et al (2014).

3.4 Operations Management

According to TQM an important key in a successful organization is to focus on processes. (See chapter 3.3.1) A process can be seen as a chain of operations. By optimizing the number and order of the operations in a process it can be optimized, it is therefore beneficial to have a strategy for this process and a plan for how to make it successful. While no development project is the same there are some general guidelines to follow. (Slack & Lewis, 2015)

Slack & Lewis (2015) presents a typical product and service development process with the steps concept generation, concept screening, preliminary design, design evaluation and improvements, prototyping and final design, and developing the operation process (see figure 13). More on this subject can be found in chapter 3.5.1. The processes for product development aims to form concept suggestions, carefully choosing some of them, testing them, and finally manufacturing them on a regular basis. (Slack & Lewis, 2015) Although the process is presented as individual steps many projects use a more simultaneous operations process. Depending on the character of the operations it can be favorable to work with them sequentially or simultaneously. (Wheelwright, & Clark 1992)

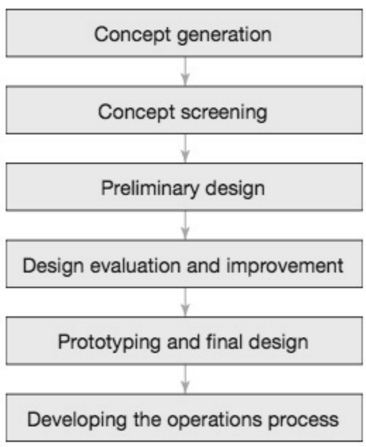


Figure 13 - A typical product or service development process described by Slack & Lewis (2015, p. 276)

When implementing a new operations strategy it is essential to go through a careful formulation beforehand. It is for example important to ensure that the operations strategy is aligned with the related strategies and that there is internal unity between related decision areas. The order of the decisions should also correspond to a suitable priority and should not compete with the more important operations in the organization. (Slack & Lewis, 2015)

3.5 Product and production development

As a part of a product development process, a production method needs to be chosen. Each production method will give different possibilities as well as difficulties that need to be taken into consideration. In this chapter, product development and its connection to production is presented.

3.5.1 Product development

The typical phases that transpire in product development projects are described in figure 13, which is a visualization of a product development process. The first phase is concept generation. This includes analyzing the customer needs, and what competitors are doing. The next phase is concept screening, which is when concepts are sorted according to suitability. Valuable criteria can be related to product strategy, pricing and realization possibility. The third step is preliminary design, which is a detailed plan of the product design. If the product is to be assembled, the plan for how the interfaces could be designed. The fourth is the design evaluation and improvement. At this point the preliminary design is improved through various testing and methods. This is done through analyzing the function of each involved part, if they fill their intended function and if it can be improved. The fifth stage is prototyping and final design. When a product design has come this far, and a design is almost set testing and prototyping is advisable as this enables certainty of the product performance. This can be done in various ways like computer models and physical prototypes. The sixth step is developing the operations process, and alerting the involved decision areas. In chapter 3.5.2, the importance of having a product and production development that is closely interlinked is described. Although the outline of an operations plan can be beneficial to have through out the development process, there are a number of aspects of the operations process that will depend on the characteristics of the final product design. Therefore this step is this far down in the product development process, functioning as the last step.

When connecting product development to the AM process, there are new possibilities that can be taken advantage of, as well as new challenges. The key thing to be aware of is that one of the main misinterpretations of the possibilities of AM is that it can solve all problems in production, as Målberg (2015) points out, see appendix G. AM does not mean that every geometry can be built, and it is not possible to just "press print" and get the physical version of the CAD-file of the intended product. There is much more though and effort that goes into planning to adapt for production through. (Målberg, 2015)

3.5.2 The connection between product and production development

If the production development process and the product development processes are independent from each other, meaning that there are not as many points of connection in the two processes problems tend to occur, and there is a risk of sub optimization. Therefore, interlinking the production and product development processes is beneficial. The design and requirements of the product produced very much affects the requirements set on the intended production system. This could include, for example, the tolerances that are set on a product or part.

To become more efficient, communication between the different functions is necessary. One example of this could be that the parts of an organization handling product development are aware of what affects the setting tolerances have on the production system while making the decisions that ultimately affect both product and production. There are a number of different models to enable this, but the underlying message is the same; integration and communication between production and product development is key. (Vielhaber et al, 2014)

Raising important tradeoffs in an early stage can be both time saving and enable not spending as much resources compared to finding these issues in a later stage (Wheelwright, & Clark 1992). This connects to what Emanuelsson (2015) mentions with engaging the production department and analyzing producibility as early as possible.

3.5.3 Designing for manufacturing

What is easily forgotten how important it is to consider the limitations of a manufacturing method when designing a product. For example Emanuelsson (2015) points out the importance of having tolerances that are manageable from a manufacturing perspective. It is not possible to produce a designed product unless it is possible to manufacture it, and that it can be assembled if needed. This can be especially important to keep in mind as the possibilities, of for example CAD software, are increasing. Almost any structure can be created in the virtual world; however there must be a manufacturing method that is able to physically create the product for it to be producible. This can connect to features in the design, but also the tolerances. If tolerances limits are too narrow there might not be a process that can achieve the set level of accuracy.

There are several methods for bringing the demands of manufacturing into the design process in an early stage. Designing for manufacturing (DFM) is a category of methods with this purpose. One DFM method aims to provide designers a set of rules to follow to ensure that they are producing products that are within the boundaries of what the manufacturing method is capable of. The concept of this method is that the design of a product needs to comprehend what the production steps downstream need, as well as what the capabilities are to make full use of the production system and increase the performance. (Wheelwright & Clark, 1992)

In successful product development, people involved in the design process such as engineers and designers are trained in taking the manufacturing and assembly into consideration when designing a product. When design for manufacturing and assembly the complexity of the design is often brought to a minimum due to the limitations of the production methods, as conventional methods are usually not as flexible in what designs they can handle without bringing up the cost of production. (Conner et al, 2014) If the manufacturing method is changed it is important to reconsider the limitations since they can be connected to the previous manufacturing method, this may affect the innovativeness of the development process.

The conventional manufacturing methods are similar when it comes to limitations compared to the limitations connected to AM. One of the main advantages for AM is the geometrical freedom (see chapter 3.1.7) and by having AM as a manufacturing option the limitations connected to other manufacturing methods can be removed. This means that the producibility of products made through AM will need to be evaluated in a different way than conventional methods.

4. Evaluation and transformation for AM

According to TQM processes and standardized ways of working are a way of achieving good quality (see chapter 3.3.1). When there is a change in the working procedures in an organization, it is advisable to standardize and visualize these changes. In the case of implementing AM as a production alternative a structured method is not yet universally agreed upon. This report presents a method developed as a part of a master thesis project, and is referred to as a method for *evaluation and transformation for additive manufacturing* (ETAM). The method is based on findings from the master thesis case study, previous research, as well as interviews with key individuals. In this chapter the method ETAM is presented in two parts, and explained in further detail. The first part evaluates whether or not AM is suitable for the organization and its current situation and the second part describes the transformation of a product for AM. A summarized version of this chapter and the ETAM method can be found, as a pamphlet, in appendix L.

4.1 Part I: Evaluation for AM

Before making a change in the daily procedures key factors involving the rest of the organization should be considered. Resent research presents important key factors for what to consider when implementing AM (see chapter 3.3.2). These key factors are external factors, AM strategy, AM technology, the AM supply chain, systems of operations, and organizational change. In accordance to these theoretical findings the mentioned key factors are divided into three blocks, which are visualized in figure 14. These blocks aim to visualize which of these key factors are the most important in the different stages of the implementation process (A to C). However, it is important to remember that all of the key factors are important at all stages, meaning that this grouping only aims to work as a guide on what to put the most focus on when.

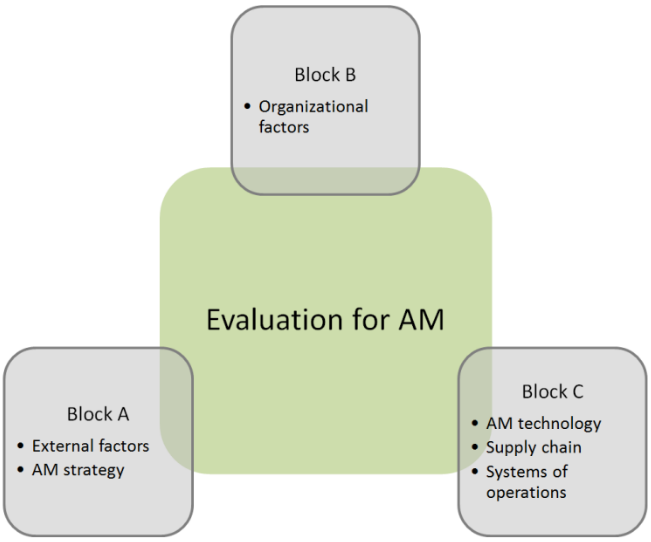


Figure 14- The ETAM method part I. Key factors for evaluation for AM.

4.1.1 Block A

Block A focuses on deciding if AM suites the organization in its current position. If it suites the overall strategy it is important to analyze in which direction the competitors are moving, and what legislations require, as well as what the customers want. An important part of this block is to evaluate the suitability of the specific product according to the three-axis model (See chapter 3.3.2). The level of customization, complexity and product volume are the key aspects in this evaluation. The results from the A block function as input to part II, where the suitable product is transformed for AM. The management should evaluate these aspects.

4.1.2 Block B

In block B the organizational structure, business size, workforce experience and skill as well as the culture of the organization is considered. The focus of this block is to map the experience and skills of the employees to see how it matches the needed level. During this block the size, structure and culture of the organization also affect the implementation process and what leadership type is suitable. (See chapter 3.3.2) Therefore these aspects need to be considered as well. This part of the implementation should be taken care of by the management team.

4.1.3 Block C

The final block includes investigating the AM technology, AM supply chain, and systems of operations. In detail this means that the available technology and supply chain routes should be investigated, but also designing for AM, and how these factors affect each other collectively.

This block is the main focus of ETAM, and in addition to the theory focus is put on the product development, to a larger extent. This additional focus is based on findings that have emerged in the case study. More details on block C is described in the next section (4.2 Part II).

4.2 Part II: Transformation for AM

This part of ETAM, (see figure 15) should function as a step-by-step procedure for AM, with focus on RM, of a previously produced product. It consists of three main blocks with included steps. The first block (C1) is an analyzing pre-phase where all the demands and limits from the product and the production are identified. The second block (C2) is the phase where a new design for the product is generated. The final block (C3) is the step where the manufacturing plan is set. Between all the blocks it is possible to decide whether or not to continue with the implementation. The choice is given to cancel if any findings show that AM is not suitable for the situation in question. The method is designed to encourage possible cancellation as early as possible in order to avoid resource waste.

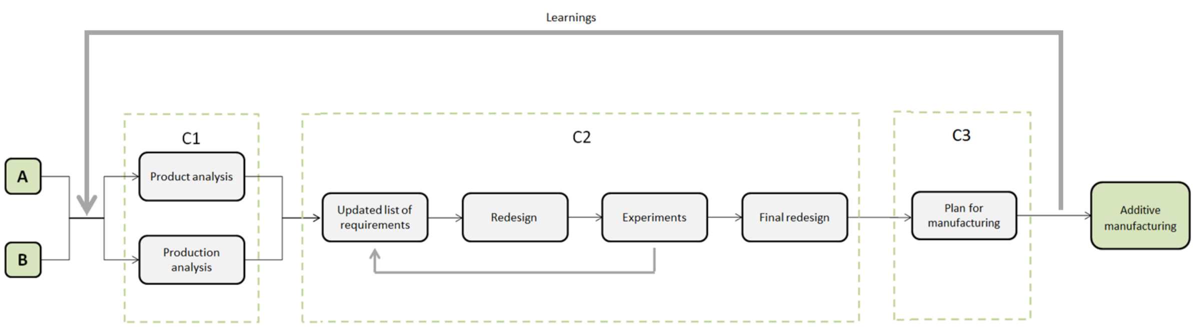


Figure 15 - The ETAM method part II

4.2.1 C1

The first two steps in part II are parallel to each other, to ensure that the process and product design are optimized and merged as early in the process as possible. A process of this kind needs to be accepted by all involved areas and a close communication is favorable. (See chapter 3.4, 3.5.2 and 3.5.3).

Product Analysis
In the product development step the current list of requirements is analyzed. The requirements that are based on the function of the product are carefully chosen and the requirements connected to the previous manufacturing method are removed. This is done in order to be able to get as much as possible out of connecting the requirements of the AM production method. In this step, possible updates i.e. new customer demands or strategic decisions regarding the design can be added such as weight reduction.

Production Analysis
In parallel to the product development step, the available production methods and their requirements are identified. First relevant AM methods should be selected (i.e powder-bed, powder feed etc.), as there are several options that will have different possibilities and limitations. When methods, which suit the product in question, are selected, the requirements of these specific methods are listed as inputs to the next step, step C2. By starting of with several options this step should eliminate the unsuitable methods for the intended product, keeping in mind that other manufacturing methods, beside from AM, can still be better options.

As AM technology is evolving rapidly, it is important to update the information in this step, each time, in order for it to be relevant. Some important matters that need to be alerted are listed below and more can be seen in chapter 3.1.7 and 3.1.8:

- Available materials
- Geometrical limitations (I.e. how much overhang can be handled, building size etc.)
- Resolution of the machine (E.g. the size of the printing beam)
- Surface finish (Can depend on the resolution, the powder grain size, etc.)
- Mechanical properties for built part
- Needed after-treatments
- Building speed

Regarding the materials it is for example important to analyze the suitability for each material option. Some materials are easier to print in than other although some material properties may make a less suitable printing material favorable anyway. If this is the case the advantages for manufacturing with AM has to be proven. (Hällgren, 2015)

4.2.2 C2
The second part of ETAM is called C2. This part consists of four steps: updated list of requirements, re-design, experiments and simulations, final design. After the experiments and simulations are done it is possible to return to the re-design phase in case the design was not

optimum. It is therefore possible to have an iterative process and the design cycle can be updated as many times as needed. However, it is important to find a suitable number of iterations to avoid resource waste. The output from this part is the final design.

Updated list of requirements

The outputs from C1, which are the requirements from the product and the production, are merged in this step. An updated list of requirements is created and used as input for the next step.

Re-design

This is the first step that changes the design of the product. It is important that the starting point for this re-designing is not the existing design but the updated specification of requirements. Using only the actual requirements encourages innovative solutions and the risk of being influenced by design decisions that are consequences of a previous manufacturing method is minimized.

Experiments/Simulations/Calculations

In this step a verification of the re-design is needed. Suitable tests and simulations are required to ensure the performance of the product. Depending on the results in this step one can either continue to the step for the final re-design or return to the step "Updated list of requirements". The latter is needed if the tests show failed results. In chapter 3.2 some possible test methods are described.

Final re-design

The final re-design depends on the results from the iterative process in C2 and functions as input for C3.

4.2.3 C3

C3 is the very last step of ETAM. After the design is set it is important to decide how to manufacture the product. If this step is reached it is possible to produce this product with AM which then needs to be planned for.

Plan for manufacturing

It is then time to decide exactly how the product is going to be manufactured: in which angle, the number of products per batch etc. (see chapter 3.1.7 and 3.1.8). AM is known for being a small batch to single product manufacturing method however to take advantage of its full potential a manufacturing strategy is needed. Regarding the number of products per batch there is a trade-off between having as many products as possible per batch and manufacturing few products at a time in order to avoid high inventory. As AM is such a flexible manufacturing method it is also possible to combine different products in one building session. This should be planned for in this step.

At this time, as a specific AM machine has been selected in a previous step, it is possible to plan more specifically for the product of choice. The exact building area is now known which makes it possible to calculate how many products that fit in one batch. Keeping in mind that products with different design can be manufactured during the same building session as long as they are of the same material.

4.2.4 Learning

After each ETAM process is executed it is important to collect the learning that have arisen during the progress. The learning is valuable for future processes and if they are not collected the new knowledge is wasted. Since AM and RM is yet fairly uncommonly used in manufacturing the gathered knowledge is low in comparison to other manufacturing methods. It is therefore extra important to collect this data and start building up a database. However, since the technique is new it is also important to stay flexible due to the rapidly evolving technique and old knowledge may soon be outdated.

4.3 Testing of ETAM

As a final step in the creation of ETAM interviews with two key individuals that both had experience in product development and producibility were interviewed. By analyzing each step of the method they were able to give comments about ETAM. The findings from these interviews can be seen in appendix B and appendix H.

The main results from these interviews were that both interviewees were positive to ETAM and its future use at SAAB EDS. The steps included in ETAM as well as the order of these steps fit into the company's way of working, which confirms the validity of the ETAM method. For example Emanuelsson (2015) says:

"In general I think that it is very good because it is exactly what we are trying to accomplish."

When analyzing ETAM in detail the order of the steps was appreciated. Especially the parallel flow in C1 and the iterative process of C2 were given positive comments. Connected to this, Emanuelsson states that it is important to ensure the quality of the product, which this iterative process can do. In general unnecessary double work can be avoided if the process is prepared properly. This can be avoided by having a close communication between product development and production but also by executing tests continuously. Petrini (2015) thought that the encouragement for experimenting was a valuable step that could add to the existing processes at SAAB EDS.

5. Weight optimization of BOR-element

The product that has been investigated is a BOR-element in an antenna. The aim of the project was to decrease the weight of the element without lowering the function. The result is based on simulations, calculations, literature studies and interviews. The progress of this project has partly followed the ETAM method and partly contributed to the structure of this method. Summaries of all the interviews can be seen in appendix B-J. This chapter presents the progress of the project that is divided according to the steps of ETAM but also the final results of the project.

5.1 Following the ETAM method

Before starting the case study some pre-work was already performed by SAAB EDS. The existing work could be compared to the work needed in block A and B of ETAM. Since the creation of ETAM and the case study were performed in parallel the results from each project part has contributed to the other. The BOR-element fits between region 3 and 4 in the three axis model by Conner et al. (2014) since it has no customization, but high complexity and a mid-range volume level. (See 3.3.2)

5.1.1 Product Analysis

To ensure that the new BOR-element fulfills the needed functions but also to encourage new innovative solutions a list of the needed requirements was created. Since SAAB EDS works within the security market the actual list of requirements is secret, also for the authors. Therefore the list of requirements for this specific case study is based on interviews with experts at SAAB EDS and the article about the BOR-element made by the inventor, Holter (2007). The requirements for the whole antenna are listed by Holter (2007) although for an element of different dimensions. Out of these the following are relevant for this case along with additional requirements given by Höök (2015):

- Frequency range: Considerably lower than 12-18 GHz.
- Outer geometries must be the same due to antenna functions.
- The element has to be possible to assemble to the underlay.

The antenna unit with the BOR-elements can be put on a boat, tracked vehicle or airplane. This leads for example to that the element must stand vibrations and be able to hold its own weight. The specific environmental data is confidential and is also not relevant for a project at this early stage. However, the electric function is important and has to be taken into consideration in all concepts. For example the BOR-elements are transporting electric signals the used material needs to possess high conductivity.

5.1.2 Production analysis

The machine that is chosen in this project is an EOS M 290 that currently is the only AM machine for metals that is available at Lasertech in Karlskoga. The details of the machine are listed in appendix K. The available materials for this machine, at Lasertech, are currently powders of EOS aluminum AlSi10Mg, EOS Titanium Ti64, EOS tool steel and EOS stainless steel 316L.

Because of the AM method of building layer by layer the material properties will be affected and the x- and y-directions are different from the z-direction, which is the building direction. If the material is heat-treated at 300˚C the fatigue resistance in the x-, y- and z-direction makes the anisotropy less, compared to for example test parts built in only 30˚C. There are also less residual stresses in the heat-treated components, as well as fewer imperfections, like pores. It is in these imperfections that create crack initiation, especially in the pore of the material. The current relative density of the material is over 99% however; in spite of the observed imperfections the material when used in SLS/SLM is very high, according to Brandl et al (2011).

Therefore EOS, which is one of the largest AM companies, uses a 300 ˚C in their process when using AlSi10Mg. The AlSi10Mg that is used at EOS has an approximate density of 99.85 %. More data about this specific process using this specific material can be found in Appendix K.

Close communication with Johansson at Lasertech gave the limitations of the production. A summary of this communication can be found in appendix F and the limitations are listed below:

- Outer wall thickness minimum 2 mm
- Other wall thicknesses: 1.5 mm
- Possibility to remove excess powder (to reduce weight)
- Maximum over hang: 30º (to avoid support structure)

5.1.3 Updated list of requirements I

The current design of the BOR-element can be seen in figure 16. It is fully solid apart from a hole for a thread insert and two guiding holes for assembling. A complete list of the product requirements combined with the production requirements can be seen in table 1. The performance due to the outer environment depends both on the design of the element but also factors from the production, therefore it is mentioned in both categories. The guiding holes are not stated requirements and will therefore be eliminated in the future design.

Because of the skin effect, the only material that is required for the transmission of the electric signal is in the outer parts of the BOR-element. The outer geometry of the BOR-element is locked, meaning that it cannot be changed. However, the design of the inside of the BOR-element is freer to change. The assumption is made that if the design can be hollowed out, there will be a need for having a support structure to ensure that the BOR-element will be able to hold its own weight, and this internal support is referred to as a support construction.

As always the cost is relevant but not the highest prioritized requirement, although it will affect the suitability for the future concepts.

Table 1 - List of requirements, prioritization rating 1 to 5, where 5 is the most important. M=mandatory requirement

	Requirement	Prio
Product specific requirements	Same outer geometry	10
	Assemble possibility	10
	Transporting electrical signals	10
	Weight reduction	10
	Inner support construction	8
	Withstand outer environment	10
Production specific requirements	Outer wall thickness: 2mm	10
	Other wall thicknesses: 1.5 mm	10
	Possibility to remove excess powder	9
	Maximum over hang: 30º	8
	Withstand outer environment	10
	Cost	7

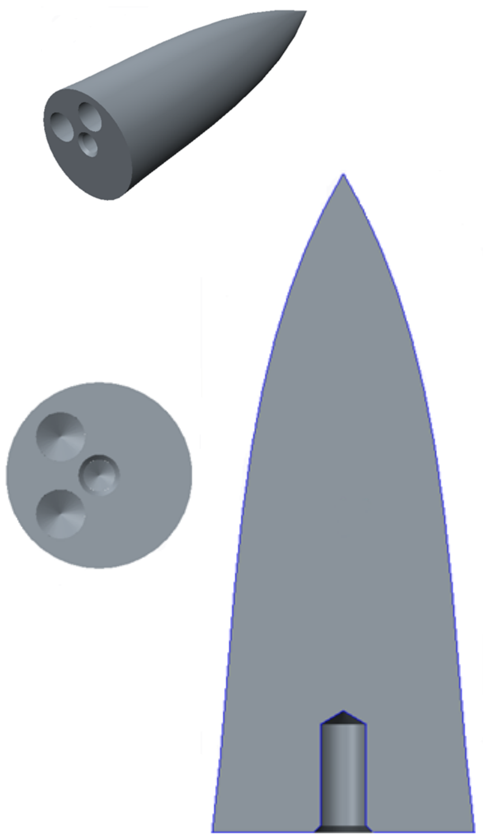


Figure 16- Current design of BOR-element

5.1.4 Re-design I

In the first round of re-design a number of new concepts were generated. Ideas and inputs from experts of both AM and in mechanical design were taken into account in the concept generation process. Among the concepts that were created with different solutions for the new design of the BOR-element, four were selected that showed the most potential. The concepts with the highest potential can be seen in figure 17.

The concept 1 is based on the concept of a bottom plate with spokes. The spokes function as supporting walls along with the hollow inside. Concept 2 is based on holes in the bottom plate. The holes are straight and placed in two circular patterns around the screw hole. The third concept builds on the same hole-pattern although the holes are not straight but follow the shape of the outer geometry instead. The fourth concept is similar to the third but consists of an inner hollow space that is connected to the screw hole. This hollowness decreases the weight of the element but needs to have an evacuation hole in order to remove excess powder from the manufacturing process; this hole is connected to the screw hole. (See chapter 3.1.2)

The two most commonly used are AlSi10Mg and Ti64. As the electrical properties are important for the function of the BOR-element, and titanium possesses low conductivity it is therefore a poorly suited choice of material in this situation. Although the current BOR-

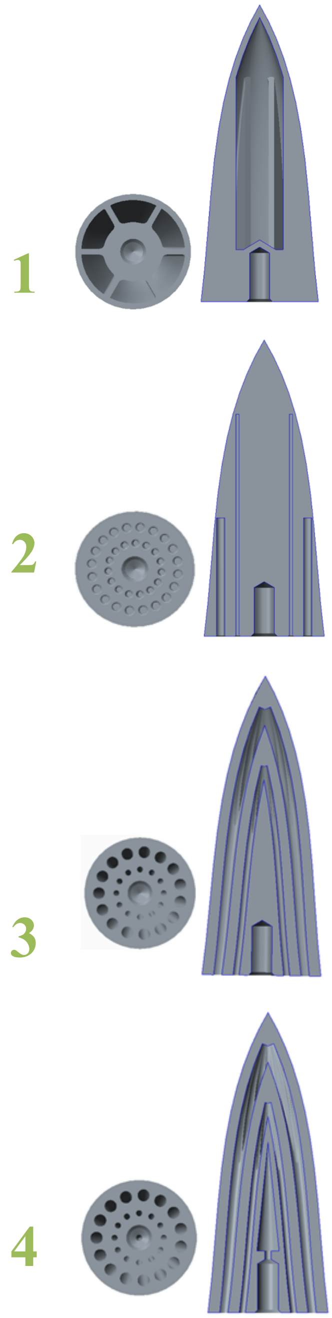


Figure 17 - Four concepts from concept generation.

element is made of steel the aluminum alloy AlSi10Mg was chosen partly because it is lighter and because the knowledge about printed aluminum is more extensive. In appendix K the chemical composition of the alloy AlSi10Mg is presented, and more information regarding the material details can be seen in chapter 3.1.4.

5.1.5 Experiments/Simulations/ Calculations I

The first round of experiments, simulations and calculations was conducted in order to eliminate concepts that did not meet the set requirements. The results aimed to give an insight into which direction to proceed in. In this round the Eigen frequency, weight and skin depth were investigated.

Eigen frequency and weight

In order to test and compare the different concepts an Eigen frequency analysis and weight simulation with AlSI10Mg (material of use with AM) was needed. This analysis was conducted together with Daniel Tidman-Lindbom, a structural analysis expert at SAAB EDS. Concept 2 was excluded at this point due to the lack of potential weight decreasing. Concept 4 was not investigated, as it was so similar to concept 3, that it was considered as unnecessary by the authors and Tidman-Lindbom.

The analysis and simulations were performed on two of the concepts (concept 1 and 3) as well as on the original design. Since the guiding holes were removed the weight comparison was made for a completely solid BOR-element, since it could have been the alternative design if it was manufactured by a conventional method.

The material choice for the BOR-element previous to this master thesis project is steel. The choice of material alone could make the BOR-elements lighter, only taking advantage in the density of the different materials, and choosing one with a low density. The assumption is made that the solid concept has the same choice of material as the new concepts (aluminum). This enables a more clear comparison between the concepts.

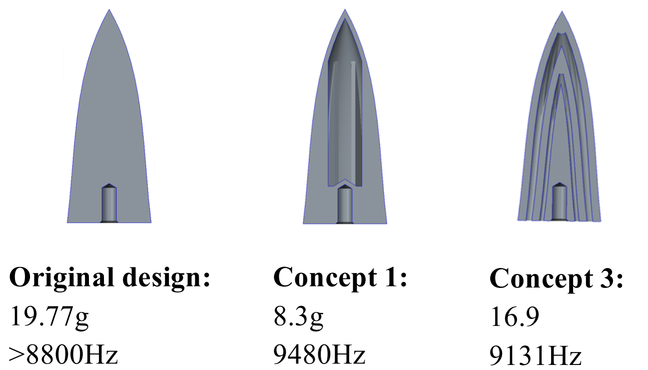


Figure 18 - Weight and eigenfrequency for the original design and two concepts.

The Eigen frequency for the solid

design was less than 8800Hz and the weight was calculated to 19.77g. The two tested concepts had Eigen frequencies of 9480Hz and 9131Hz. The weights of each concept were 8.3g and 16.9g. These results can be seen in figure 18.

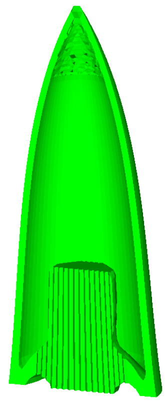


Figure 19 - Result from topology analysis

Structural topology optimization

A topology analysis was also done at this point. The conditions for this analysis were as follows:

- The outer geometry is fixed, continuous and smooth
- The outer border of the bottom surface is in contact with the underlay
- The minimum wall thickness is 2 mm
- Assembling onto the bottom plate by screw or similar

The results from the analysis can be seen in figure 19 and shows a large hollow space inside the BOR-element but also ditches on the bottom plate. These ditches exist in order to center the forces to the outer circle of the bottom plate. The recommended wall thickness is 0.5 mm.

Skin depth

At an early stage the importance of having a fine surface finish arose. The function of the element in terms of skin effect and noise could be affected. Since one of the drawbacks with AM is the sometimes-poor surface roughness this had to be investigated.

The skin depth was calculated according to Eq. 1 (Chapter 3.2.2) with material data according to aluminum and the given frequencies that this specific BOR-element operates in. These numbers give the skin depth value of δ_1 and δ_2. Thereby it is important that the wall thickness is at least δ_1 in order to not disturb the low frequencies and the surface finish must be finer than δ_2 to avoid disturbance on the higher frequencies, (see figure 20). Compared to the specific data of the used machine (appendix K) the real surface roughness is much higher than the theoretical skin depth. The skin depths δ_1 and δ_2 were considerably less than 6-8 μm which is the average surface roughness for products produced through AM This would mean that in theory the surface roughness produced through AM would not be acceptable. However, this needed to be investigated further.

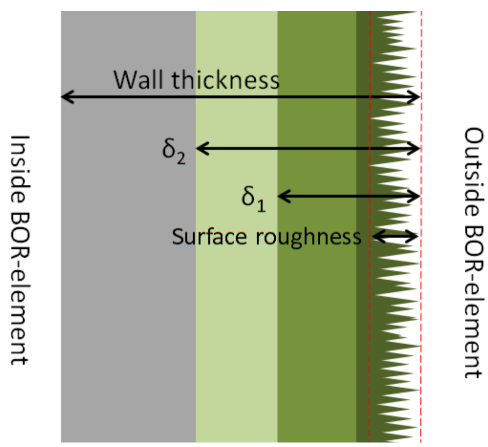


Figure 20 - Explanation of how the skin depth δ can be affected by surface roughness and wall thickness.

A complementary analysis of the antenna functions was made as well. This analysis was based on a Huray model (see 3.2.3) and Andreas Wikström was asked to perform this analysis. Wikström's result showed that the normal surface finish for the AM machine that Lasertech uses is fine enough and will not affect the performance of the whole antenna. Details of this analysis can be seen in appendix M. According to the antenna expert Höök (2015), the assumptions made in a simulation using the Huray model should represent a much worse scenario than that of the AM material (see appendix M). This would mean that AM can produce a sufficient surface roughness for this situation, it is thereby contradictive to the skin depth calculations.

5.1.6 Updated list of requirements II

The topology shows that the need for support constructions in connection to the hollow volume is less than expected. To optimize the design a circular ditch in the bottom plate is advisable. These two factors should be taken into consideration and are shown in an updated list of requirements. The new list can be seen in appendix N.

Due to the fact that the results regarding the surface roughness were contradictive it was not obvious if the roughness would affect the signal or not. Therefore the possibility to make the surface roughness finer so it would not disturb the signal should be investigated. Several options of after-treatment were discussed. The current design is manufactured by turning and has an accepted surface roughness therefore the possibility to after-treat by using turning should be investigated. This matter also led to an added requirement for surface roughness in the list. This factor had previously been included in "transporting electrical signals" together with material specific properties but seemed to be important to have on its own.

5.1.7 Re-design II

With the topology analysis in mind a new concept (concept 5) was created in order to be as similar as possible to the suggested topology design. As can be seen in figure 21, the design contains of a large hollow space inside the part, a circular ditch is added to the bottom plate to center the forces to the outer circle. Two holes are added in the ditch so that the excess powder can be evacuated from the hollow space. (See chapter 3.1.2). The two previous and still remaining concepts are not similar to the topology result and were therefore put on hold until the suggested topology design was verified.

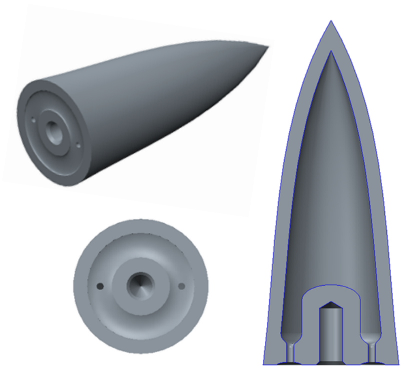


Figure 21 - Concept 5 from re-design II

5.1.8 Experiments/Simulations/Calculations II

At this point concept 5 was sent to Lasertech for an evaluation with the manufacturers. A first try of manufacturing showed that the ditch was too small to handle and beard was created. This design caused a more difficult after-treatment for removing the mandatory support structure.

In order to investigate the possibility of using turning as an after-treatment Åke Nilsson at Sandvik AB and Tommy Gustavsson at Husqvarna AB were contacted. Sandvik delivers turning tools and are therefore experts within the field and Husqvarna had manufactured prototypes of a similar product before. The concern was whether or not the hollow design could stand the strain of the turning forces. Although the exact forces were unknown it was stated that a BOR-element designed with a hollow inside should stand these forces. (Nilsson, 2015) (Gustavsson, 2015)

5.1.9 Updated list of requirements III

One early requirement from the manufacturer was a wall thickness of 2 mm for outside walls and 1.5 mm for internal walls. Due to the fact that AM is considered being a not fully explored technique the system was considered to be not fully iterated. The manufacturer showed some indications of being able to produce thinner walls than was first said. Therefore this requirement was considered to be less strict than before. Instead a new limitation called "Manufacturing resolution limitations" was added to represent the possible resolution advantages and disadvantages. The new changes in the list of requirements can be seen in appendix N.

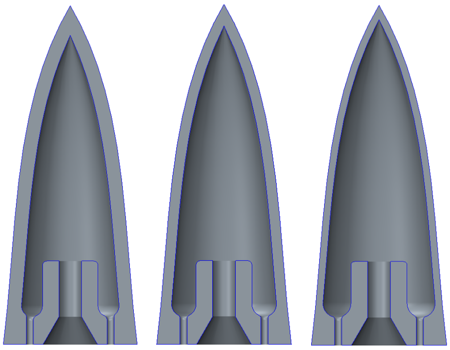


Figure 22 - Concept 6 with three different wall thicknesses: 2mm 1.5mm and 1mm.

5.1.10 Redesign III

The third re-design was based on the input from the updated requirements from the manufacturer. Some modifications were needed on the ditch. The idea with the ditch was to center the forces to the outer surface. Since the ditches were difficult to manufacture a sixth design was created (See figure 22). This design is without the ditches but has a cavity around the screw hole. This spreads the forces to a larger part of the element that with the ditches however it is still centered on the outside of the element. When the screw creates offsets the risk of the offset to touch the underlay, and thereby take up the forces, is planned to still be very low.

Due to the eased requirement of the wall thickness three variants of the new concept 6 was created with thicknesses of 2 mm, 1.5 mm and 1 mm. All these can be seen in figure 22.

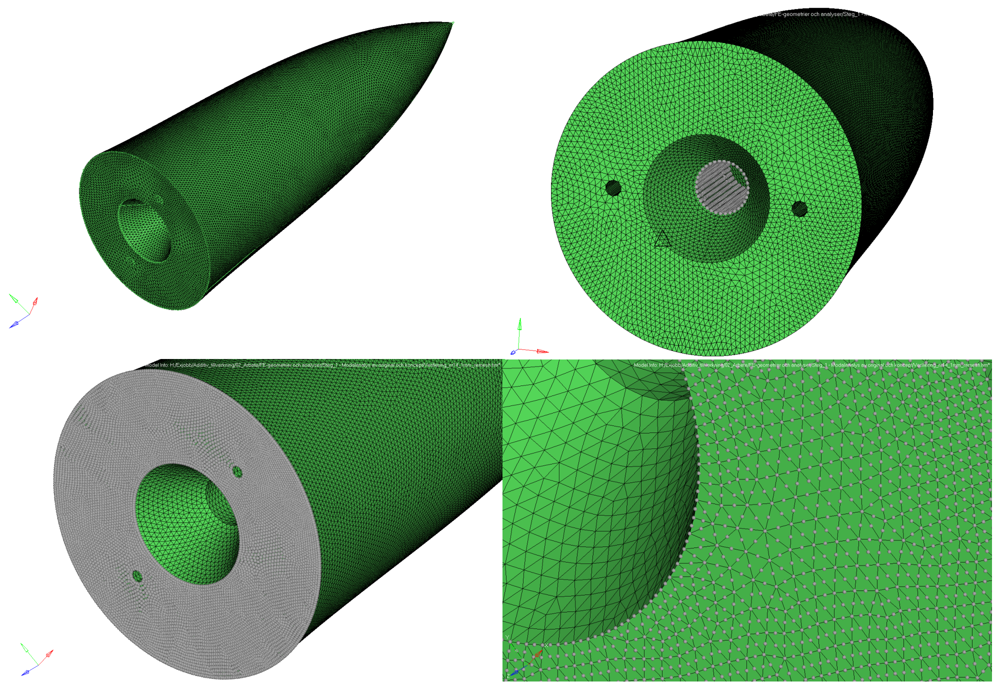


Figure 23 - First picture showing concept 7 with used mesh. Second picture shows the nodes used for the screw's boundary conditions. The bottom left picture shows the boundary conditions for the fixation from the assembly. The bottom right picture shows a close-up of the nodes.

Another feature in this design was the removed top of the screw hole. Initial analysis showed that this feature was unnecessary and removing it would both make the removal of the excess powder easier and reduce weight.

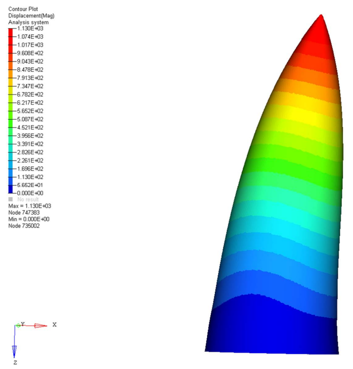


Figure 24 - Eigenfrequency 1 for concept 7, oscillation in x-direction (red arrow).

5.1.11 Experiments/Simulations/Calculations III

As a third step of simulations an Eigen frequency analysis was performed on concept 6 with wall thickness 1 mm. It was stated that if this wall thickness of 1 mm can stand the forces the other two could as well.

Figure 23 shows how the mesh and the boundary conditions for this simulation looked like. It consisted of 392 038 elements and thereby 614 843 nodes. The bottom plate's nodes were fixed in all directions to simulate assembling to the underlay and the nodes in the screw hole were fixed in z-direction. The affected nodes can be seen as the grey dots in figure 23. The nodes are designed to be fix in z-direction, visualized by the blue arrow in the coordinate system.

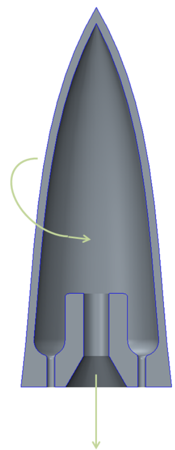


Figure 25 - The boundary conditions for for the BOR- element.

The Eigen frequency for the concept was calculated to be ~9998 Hz for the first and second frequency (x and y direction) Figure 24 illustrates Eigen frequency 1 but amplified to get visual effect. The third and fourth frequencies are 21180Hz, which are the "double frequencies" in direction x respectively y. The fifth frequency simulates the frequency that shows when the product is rotating around its own axis and is as high as 29620 Hz. The value for the first frequency is higher than the current, solid concept. As can be seen in chapter 3.2.1 it is preferred to have a high eigenfrequency.

The BOR-element will be exposed for two different boundary conditions (figure 25), a force cause by the pulling of the screw and a torque from the assembling that affects the element even when it is fixed.

Figure 26 illustrates the offset and the tensions caused by the screw forces. The maximum offset is 7.1 µm and the maximum tension is 178 MPa in the most affected areas. The offset is

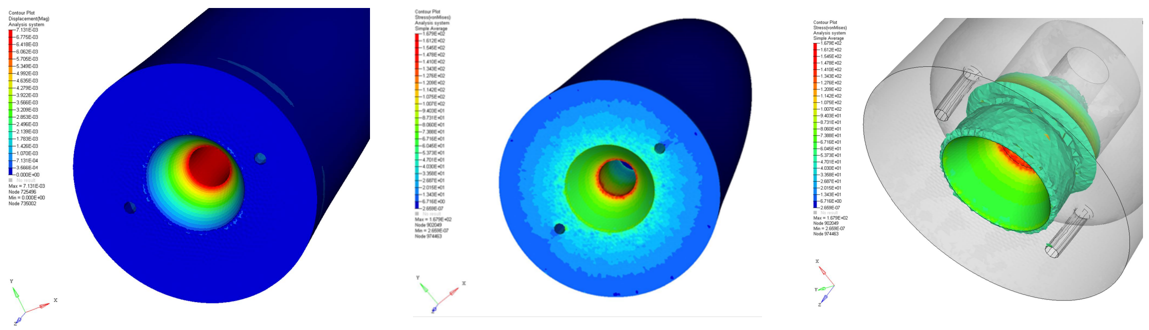


Figure 26 - First picture shows the offset caused by the screw. Second picture illustrates the tension caused by the very same and the third picture shows the tensions that are higher than 50MPa.

acceptable since it is small in comparison to what the design can tolerate before it gets in contact with the underlay. The tensions are also small in comparison for what the design can handle. The yield stress for AlSi10Mg is >200 MPa and in the third picture in figure 26 it is possible to see the spread of the tensions >50 MPa. It shows that the affected area is small and the risk of yield is low. The most critical area is the screw hole.

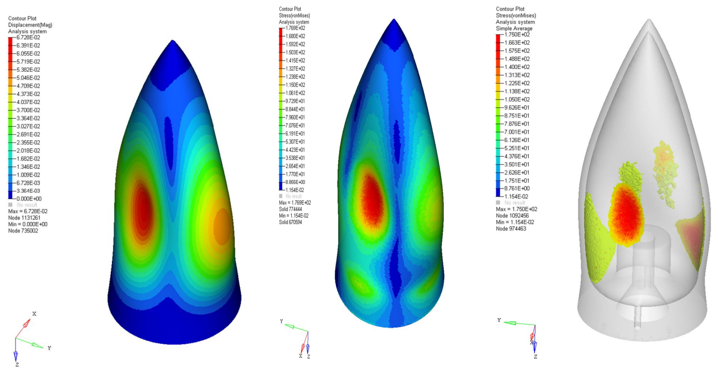
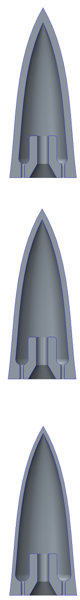


Figure 27 – Figures showing the offset caused by the force due to assembling, although enhanced. Second picture shows the tensions due to assembling and the last picture is the same although tensions less than 100 MPa are filtered out.

When simulating the effect of the assembling an area of nodes symbolizing the finger of the assembling operator was used. The force used was 860 N per finger, which is an assumption with high margin. The result of the assembling is a torque of 662 Ncm, which is also much higher than can be expected in reality. Figure 27 shows the offset and tensions caused by the assembling greatly amplified for a visual effect. The first picture shows the offset due to assembly, the second picture shows the tensions caused by the same with a maximum pressure of 177 MPa and the third picture also shows the tensions although only the tensions larger than 100 MPa. These results show that concept 6 can stand the stress that occurs from assembling.



2mm: 11.71g

1.5mm: 10.03g

1mm: 8.17g

Figure 28 - The different weights for each wall thickness of concept 6.

The different weights for the three different wall thicknesses can be seen in figure 28. As can be expected the weights are lower than the solid design.

Prototypes

Concept 6 was ordered in 13 samples. Three complete prototypes of each size, one of each size with a cross section and one element that is after-treated with turning for a better surface roughness were ordered. The after-treated prototype was designed with a wall thickness of 2 mm. A picture of produced BOR-elements is shown in figure 29. These prototypes were weighed, CT-scanned and analyzed through microscope and although the results from the tests can be seen as indications the tests are not scientifically proven due to the small sample size.

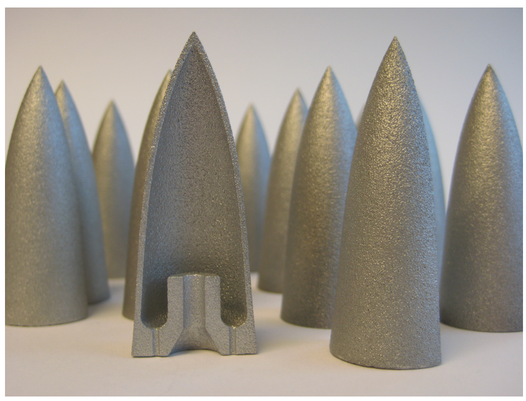


Figure 29 – Some of the printed prototypes.

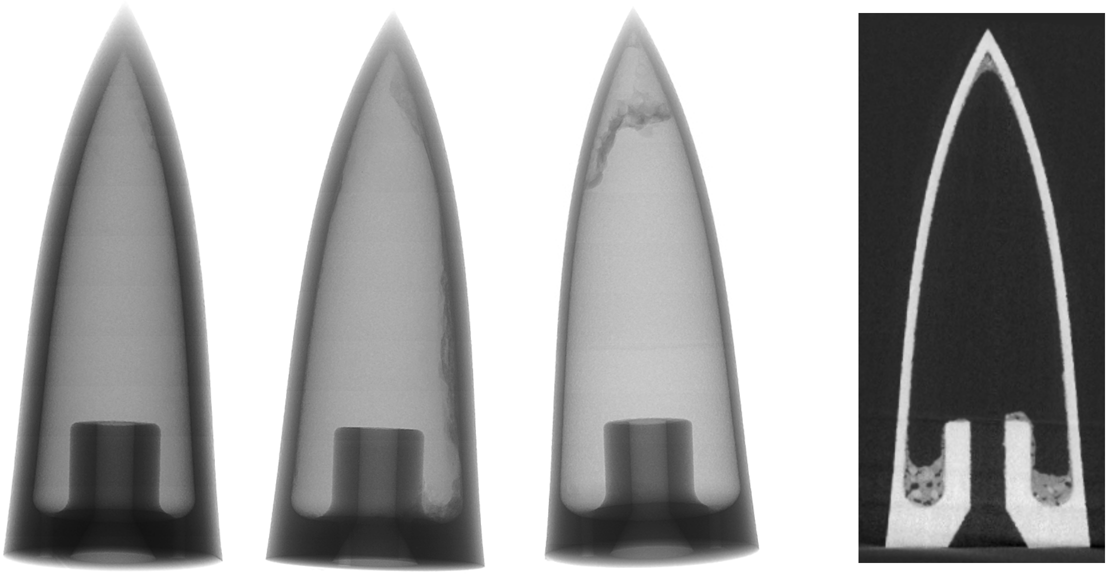


Figure 30 - Scanning of three prototypes based on concept 6. Unmelted powder is visible in all prototypes although in varying amount. The figure shows the three wall thicknesses 2, 1.5 and 1 mm. To the far right a scan showing powder on the bottom of the hollow space of the BOR-element.

ICT-scan

The first test was an ICT-scan on the elements. One scan of each wall thickness can be seen in figure 30. When printing a metal component the excess powder needs to be removed after the process is done (See chapter 3.1.1). In some situations the powder can get stuck inside an internal geometry. This applies for this specific case.

Figure 30 shows that the powder is placed both on the side of the inner wall of the BOR-element (second picture) and on the top of the element (right picture). Also examples of powder in the bottom of the hollow space occurred (see figure 30). On the nine tested elements the wall thickness seemed to affect the amount of powder that is not melted. The thicker the wall the more powder seemed to have been successfully removed. According to Johansson (2015) one reason for the thin wall thickness to cause more powder may be due to that the process of removing the powder involves a water bath and the lightweight caused the elements to float rather than sink, which complicated the removing process.

Weighing

The prototypes were weighed in order to compare the actual weight with the expected weight from the computerized analysis. The complete elements were weighed but also the halves with the cross-section. The average weight for the element with 2 mm wall thickness is 11.29 g. For the element with 1.5 mm wall thickness the weight is 9.63 g and for the 1 mm thick element the weight is 7.97 g. This result shows that the weight decreases by ~1.5 g when the wall thickness decreases by 0.5 mm. The leftover excess powder most likely causes the difference between the weights of the elements with the same wall thickness. Neither the weight difference between the after-treated can be pointed out as different to the others. All of these weights are lower than the one for the current solid design. The new design with 1 mm wall thickness weighs 41 % of the original solid design. The results from the weighing can be seen in appendix O.

The theoretical weights of the BOR-elements were retrieved in the CAD-software with the assigned material, and were compared with the actual numbers that were collected through weighing the printed parts. These showed to be relatively similar; especially for the two smaller wall thicknesses. For the elements with a wall thickness of 2 mm the theoretical weight was higher than the real weight, even though these did not have as much excess powder in them. However, this does not need to indicate any pattern, as the sample size is low and no valid conclusions can be drawn from this.

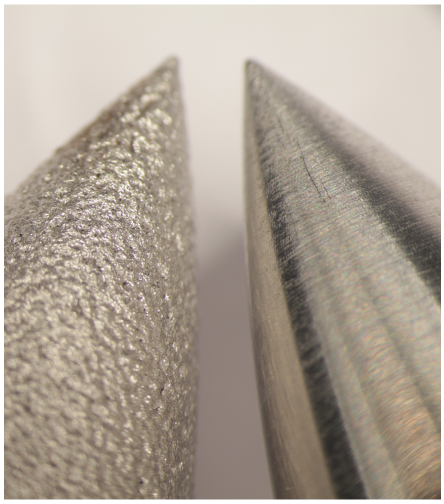


Figure 31 - Picture of the surface finish for a printed element and an element after-treated with turning.

Surface analysis

The surface of the elements was studied in a microscope. Both the original printed surface and the after-treated surface were studied and the difference between them was visual. Figure 31 shows the difference between the surfaces.

5.1.12 Final re-design

To sort among the concept a PMA was conducted (See chapter 3.2.5). By using the list of requirement a PMA was possible to create however, the requirements with prioritization 0 were removed. The original solid design was used as the baseline and weighed against the four final concepts: Concept 6 with three different wall thicknesses and the concept 6 with after-treatment. By weighing all the requirements it became clear that the design with a 1 mm wall thickness was favorable. The table also shows that the after-treated concept is better than the non-after-treated concept of the same wall thickness. This indicates that an after-treated BOR-element with a wall thickness of 1 mm would be even better. The complete PMA can be seen in appendix P.

5.1.13 Plan for manufacturing

As with all manufacturing processes the AM process need to be planned as well. Although the manufacturing area for AM is small it can be valuable to manufacture in small batches rather than one-by-one. The machine that Lasertech uses has a manufacturing volume of 250x250x325 mm, where the building area is 250x250 mm. Due to confidentiality; the diameter of the BOR-element is assumed 20 mm. One can thereby fit 12x12 elements in one batch in optimum conditions (see figure 32). However, manufacturing ~140 elements might not be optimum in terms of other aspects. If one antenna contains 200 elements one could either process 140 at the first round and the remaining 60 pieces the second session. It is also possible to produce for example 100 at each building

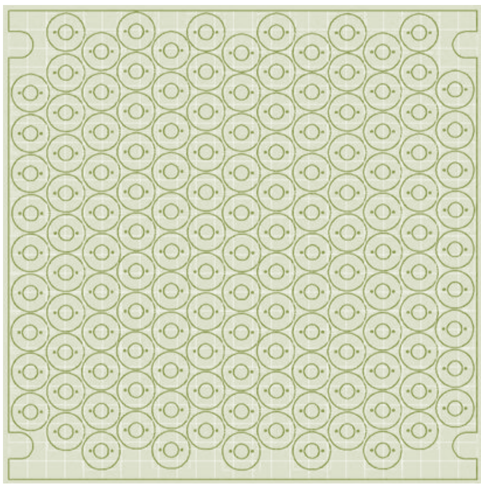


Figure 32 - Picture showing how many BOR-elements that fit on the building area. In this picture the elements are 139 but some more may be squeezed in.

session. Since it is possible to manufacture completely different geometries at the same time as long as it is the same material (see chapter 3.1.7). Therefore it can be beneficial to manufacture for example 100+100 elements and leave space to other products instead of 140+60.

5.2 New concept vs. old concept

To evaluate how favorable the new concepts are in comparison to the original a few key factors were chosen to facilitate the evaluation. The reason AM was considered as an option for this product was mainly due to the need of lowering the weight of the BOR-element. Therefore this is included in this final comparison. A precondition for being able to accept the new design was that it could serve the same function as the existing BOR-element, even though another manufacturing method was used. This means that it is important to compare the ability to fill the intended function, in this case the ability to facilitate the sending and receiving signals at a set band of frequencies.

The best two versions of concept 6, the one with a wall thickness of 1 mm, and the one that had been after-treated using turning, were compared to the original design, without the two guiding holes (See table 2). The weight for the concept with wall thickness 1 mm is 8.169 g which is a 59 % weight reduction compared to the solid concept if assuming that the material is the same. The price was chosen to be kept secret however a comparison shows the difference between the alternatives. The function could not be measured but the analysis showed that concept one should have a lower function than the original concept but the turned concept has the same surface finish and therefore the same function. However, whether or not the lower function from the non-after-treated concept will matter or not is still unknown.

Table 2 - Comparison with the final concepts

	Solid concept	Concept 6, 1 mm	Concept 6, 2mm, turning
Weight	19.77 g	8.169 g	11.54 g
Cost	X	~ 2.5X	~4X
Function	Y	Less than Y	Same as Y

The concept 6 is favorable only through weight reasons. On this concept the weight is reduced to around half the original weight, and this is under the assumption that the material choice is AlSi10Mg. If comparing to a solid BOR-element that would have the same material choice as the original BOR-elements by Holter (2007), which has a higher density, the difference would be even greater. The function for the concept 6 that was after-treated with turning is the same as the original, but more costly as another step is added to the production process. The untreated version of concept 6 is possibly less due to surface roughness although it may be sufficient. The cost is higher for the other concept 6 as well.

If needed, a concept 6 with a wall thickness of 1 mm would be after-treated with turning. This would make it more expensive, but it would mean a minimum weight, as well as a function that is the same as the original, assuming that this is a necessary choice. This would be the most expensive version, but it would maximize the weigh reduction, while at the same time ensuring the function quality.

6. Discussion

In this chapter, the ETAM method that has been developed in this master thesis project is discussed, both in regards to the impact that it could have as well as how the method should be used, along with recommendations for usage. The case study where the authors led a project, following the ETAM method, is discusses in terms of the impact it has, also along with recommendations.

6.1 The ETAM method

The ETAM method enables companies to evaluate the suitability of additive manufacturing (AM) for their specific situation. Since AM is not suitable for all businesses and situations, at any stage in ETAM, the decision can be made to terminate the project. The key thing in a case like that is that this is identified as early on as possible, which is something that ETAM allows by highlighting the key factors in implementing AM in a set order.

6.1.1 The stages of ETAM

By following ETAM a company can have a structured way of working when making an initial investigation regarding if AM is suitable for the company in question. To produce a product using AM the value for the customer needs to be kept in focus. The possibility to use AM is not always aligned with the company strategy and does not necessarily give the wanted results. By keeping these aspects in mind there is much to gain both for the company producing but also for the end customer that is more likely to get a better product. This is made clear in the ETAM, as it in step A of the method describes that this aspect should be investigated. By looking at the needs of the external factors, and the strategy of the company that is looking to possibly implement AM, the ETAM method ensures that this vital area is highlighted and investigated before doing any drastically changes. By being prepared and making an informed description about AM before making radical changes or investments, this could save companies both time and money as well as avoiding creating strategic misalignment.

By evaluating the current state at the company; it is possible to see how ready the organization is to start with AM as a production method. This is highlighted in step B of the ETAM method, where a mapping of the resources is the main focus of the step. By analyzing the competence at the company appropriate measures can be made to prepare for an implementation of AM at all stages of the organization. This is needed to be able to handle the new way of thinking and working that is connected to AM. By doing this in an early step of the implementation process, it can create a situation that is more welcoming for everyone to be involved, which is important when trying to deal with possible resistance to change. Also, by preparing for AM in this early stage, the ETAM enables the company to be able to better handle AM as a production method and the transition (from for example only using traditional production methods) is made more structured which could mean that it is more likely to succeed.

To truly be able to reap the benefits of this new production method, AM, there needs to be an understanding of that the limitations and drawbacks are to all production methods, as well as benefits and possibilities that could be taken advantage of. Only then will the real value of

AM as a production method be utilized. ETAM enables this through step C1 which deals with the demands of the product as well as the production, in parallel to each other. The fact that these two are investigated and adapted for in the same stage enables these development processes to interact in a natural way, making sure that the production and product are suited for each other and encourage close communication.

The product that is being investigated for AM receives an updated list of requirements, which is one of the major benefits of using ETAM. In the industry it can easily happen that features of a design can be left through several cycles of redesign, simply by routine. What ETAM does is looking at the actual demands; disregarding features from for example previous production methods. The redesign is part of step C2 in the ETAM process. Topology optimization and FEM analysis are among what could be used when redesigning the product, which can enable using the benefits of AM as a production method, as a rapid manufacturing (RM) technique. As the preparations have already been made by making sure that there is a value in using AM for the customers, that it is in alignment with the strategy and the culture of the company, and that the personnel is educated and have the right tools available, this process will be more efficient than it would without ETAM.

When a final design is created, the final plan for manufacturing can also begin which is described in the step C3 in ETAM. As the requirements from the production is incorporated in the design process, this last step will be less of a challenge as product and production is already merged. Also, as the suppliers are already involved in the early stages, identifying a supply network that is suited to aid the production can be well on the way, and this step is only to finalize these specifications.

As the market is new and developing rapidly the learning aspect is an important part of the ETAM method, as the variables then especially from the production can change quite rapidly. Also as the industry is still discovering how to use AM as a production method it is possible to push the limits of what is possible to create even further, as a part of this learning process. This is something that the authors of this master thesis got to experience first-hand, which meant that the redesigned part form the case could become even thinner than what was originally suggested. It is important that the information on which to base the new constraints on is updated, in order to take advantage of the fact that there are so many new opportunities and that the list is growing.

6.1.2 How to use ETAM

Many organizations are striving for good quality throughout the organization. One important aspect of this is to focus on processes (see chapter 3.3.1). ETAM is a process that should be used when there is an interest in using AM as a RM technique. This means that ETAM is suitable for investigating the possibility of AM and the redesign process of AM, to create beneficial conditions for this production method. All projects are unique however a guiding process will facilitate the progress of a project. Although there are some general product development processes (See chapter 3.4) ETAM contributes with more specific guidance mainly for projects involving AM and metal products. ETAM enables the product development to be more effective, and therefore faster. However, both before and during

ETAM it is important to remember to weigh the advantages of using AM for the specific product against the cost of having employees working with a conversion for AM. Although ETAM will facilitate this process the cost of executing the project has to be accounted for.

ETAM was tested on a redesign of a metal product, which it proved to be well suited for, however, it can also apply to new product design when adapting for AM or for products of a different material. In that case it should be in combination with an even more thorough conceptual modelling phase and some project specific modifications can be required.

The steps A and B of ETAM should be handled from a managerial position as it deals with the overall vision and course of actions. All steps in block C can all be handled by engineers and designers working in the product and production development process, as this step is more specific to these two aspects.

6.1.3 Recommendations regarding ETAM

The general recommendations for the future work with ETAM, is to further investigate the effects of the supply chain, and making a structured add-on for the ETAM method in what to investigate in regards to this aspect. It could be beneficial to look into how to utilize the possibilities of AM, such as creating the opportunity to be closer to the customer, which could affect where production sites are located, suppliers, whether to outsource or keep production in-house etc.

More specific recommendations for SAAB EDS are to begin implementing the ETAM method in their processes connected to production. Further education in the ETAM method and of AM in general could be a next step for SAAB EDS. As a part of this further education in ETAM a pamphlet summarizing the method was developed to function as an aid in future AM projects.

6.1.6 Sustainability

By using ETAM and the structured way of working that it provides, there can be many types of benefits for the user. ETAM can add to the sustainability financially, environmentally and socially as these aspects were taken into consideration in the development of the method, which is reflected in the process. There is a financial aspect of using ETAM because of the resources that can be put into an implementation process can be costly, and it is important to make sure that time is spent on work that will have a value. Just having a CAD model and printing it, much like has been done when producing prototypes in plastic through AM will not provide an optimal production process when working with real end use parts. Creating awareness of the process of AM and busting the myth that it can solve all production and design problems is one of the main benefits of using ETAM. Environmental sustainability is an important aspect of the ETAM method as it allows companies to be more efficient in their product and production development to take advantage of the benefits of AM such as material efficiency, weight reduction, resource efficiency, part flexibility and production flexibility.

Due to the fact that ETAM enables less of a trial-and-error approach to product development, even though the production method is quite new, there is an aspect of both financial and environmental sustainability that accompanies the use of ETAM. Less failed development projects lead to less wasted resources.

6.2 The Case study of the BOR-element

The BOR-element qualified as a possible candidate for being produced through AM because of the need for weight reduction, which was deemed very difficult to achieve by any other method. As the strategy of SAAB EDS, and the high technology environment that is present in that organization, welcomes an AM process the demands from the A and B step of ETAM was accounted for, and the process of implementation could start. Some of the steps still needed to be accounted for. As the time for the master thesis project was limited not all aspects could be taken into consideration. For example, the mapping of the knowledge at SAAB EDS and the available software etc. are aspects that should receive more attention in future projects. However, as the aspects of the redesign were selected as more important, the case still gives a good testing of the ETAM process. Creating a new and improved version of the BOR-element that now meets the requirements that are set by the function and of the AM production method was also a valuable result.

By using ETAM in the process of developing a new version of the BOR-element much time could be saved as the contact with the supplier, Lasertech, could be limited to constructive and efficient data collection. Through working together in a structured way the time management of the process could be more efficient and increase the possibility to get the most out of the process.

6.2.1 Choosing AM method and material

The material and type of AM method was selected on the basis of what would be the most beneficial for meeting the requirements of the product in terms of its function. However, the search was limited to the materials and machines that were in the TTC collaboration, meaning the EOS machines at Lasertech. EOS M290 stands for such a large portion of the market, and has a relatively wide range of materials for their machines this would not necessarily be viewed as a large limitation.

When choosing the material the decision was limited to the metal powders that were available at Lasertech. Out of these available materials, the options titanium and aluminum were the two that stood out. One of the most beneficial materials to use in AM is titanium as it is expensive and hard to machine using traditional methods, meaning that AM is a strong candidate when working with this material as these problems are basically eliminated in this process. The problem with titanium, if it were to be used for the BOR-elements, is that the conductivity is not sufficient. The aluminum material AlSi10Mg was chosen for its advantageous conductive properties, as well as the low weight of the material. Despite the fact that aluminum takes long time printing and is easy to cut in it is the strongest material candidate.

The fact that this decision was limited to the TTC collaboration meant that there is a possibility that there are better options of both material and AM machine. However, under these circumstances the choice made was the best available one.

6.2.2 Wall thickness

In our case there were several occasions where the limitations from the production method were challenged. For example with the wall thickness of the BOR-element, the first constraint from the production was a minimum wall thickness of 2 mm. According to the calculations that were performed, by the authors, regarding how deep into the material the skin effect is active for the frequency used, the walls only needed to be as thick as 2.0 µm. This means that for the actual function of the BOR-element (other than being able to withstand the demands of the outside environment) the weight of the BOR-element could in theory be reduced significantly compared to the solid version that was the existing concept.

According to the calculations of what wall thickness was possible in order for the BOR-element to withstand the demands of the outside environment, the walls could be as thin as 0,5 mm. This means that the limiting factor was the production in this case. During the course of the project this requirement was tested, by actually trying to print BOR-elements with a wall thinness of 1,5mm and 1mm. This shows that because the method is so new and that there is still so much to discover about what is possible when using it. It can be very beneficial that product and production development have a close communication. In the case of this master thesis, it meant being able to reduce the weight even more than what was first considered possible.

6.2.3 Surface roughness

During the progress of the importance surface roughness of the elements turned out to be a central factor to investigate, as this would determine if AM could fulfill the demands on the function. This was analyzed in different ways and the results were contradicting. As a part of this the possibility to perform an after-treatment arose.

Contradicting results

In the iteration between redesigning and performing calculations also led to challenges in the demands on the product. The surface roughness was a large portion of what needed to be investigated. The EOS machine and the metal powder that was used are known for having finer grains, creating a smoother surface roughness than for example the Arcam machine. Although the Arcam machine is not an option when working with AlSi10Mg, it is worth mentioning that this choice does affect the surface roughness parameter as well.

During the investigations calculations were made on the authors' request, to see how much the surface roughness affected the signal of the antenna. These calculations were based on the Huray model, which approximated the surface to be much worse than that of SLS, the AM method that was used for building the BOR-elements. In the interview with the antenna expert Anders Höök (see appendix E) it was confirmed that since calculations with the Huray model did not show any noticeable effect on the signal, it was very unlikely that the BOR-elements which do not operate on a critical frequency for being sensitive for this kind of disruptions.

As there were contradicting results from the two calculations regarding the effect of the surface roughness on the signal, two parallel paths had to be taken. The first was to assume that the surface roughness of AM was sufficient for transmitting a signal, which would imply that the demands on production would take AM into consideration. The second was to assume that the surface roughness of AM was not sufficient for transmitting a signal, which would mean a need for either finding a way to increase the surface quality or excluding AM as a possible production method. The inner surfaces were not critical to the function, and therefore excluded from the possibly stricter demands. One way to increase the quality of the surface roughness would be to after-treat the elements. As turning is the current manufacturing method, using turning as an after-treatment method would enable the results to become as close to the current surface roughness as possible.

Further tests of surface roughness
As there is not yet a fully constructed underlay for the larger BOR-elements, the real signal function could not be tested. There is, as was previously mentioned, a smaller version of the BOR-elements that does have a constructed, physical underlay, on which these smaller BOR-elements can be mounted on. Therefore, it is currently possible to conduct tests on these, of the signal function. The smaller BOR-elements might be more sensitive the surface roughness effecting the quality of the signal, because of the high frequency that they operate on. This means that if the tests show that one surface roughness is sufficient for the small elements the same roughness will be more than enough for the larger elements. However, even if tests performed on the smaller BOR-elements would indicate poor results in the signal this would not necessarily mean that the same thing would be true for the larger BOR-elements. This is worth noting, for the future work with the BOR-element.

6.2.4 Sustainability
The solid BOR-elements which were the starting point of the case of this master thesis are theoretically possible to use, as it meets the set requirements like for example the Eigen frequency is higher than the minimum etc., meaning that it would in theory withstand pressures of the outside environment. However, as the weight reduction was a critical demand, this need to be weighed against the increase in production and product redevelopment cost that this change of production method causes. Financially the BOR-elements are more expensive then when using turning, however turning only externally was not considered an option for the larger BOR-elements if the weight should be reduced. This would require a much more complicated process and will probably include more steps in order to be able to create this ‘impossible shape’.

The comparison in chapter 5.2 shows that using AM is not the cheapest alternative in terms of manufacturing cost. However, if the weight reduction is critical it is relevant to compare the importance of low cost to the importance of the weight reduction. The same goes for comparing manufacturing methods that can achieve the same weight reduction as AM but may have other shortcomings. In this case the weight reduction was considered to be very important and therefore a comparison between the AM method and an alternative that also can manufacture a weight reduced BOR-element is more relevant than comparing to a manufacturing alternative for the current solid design. Manufacturing a hollow design would surly be a complex process without AM and the difference in costs could very well be less than in the made comparison.

Because of the reduction of weight in combination with the fact that the AM process is able to use basically only the material that is needed, the financial aspect of using AM can be beneficial both from a financial standpoint but also from an environmentally sustainable one. As was mentioned in chapter 3.1.7 the resource efficiency, i.e. use of manufacturing tools, is more beneficial for AM than for many traditional methods. This also adds to the environmental and financial sustainability of using this production method.

This could be more financially sustainable than for example sending an entire team of engineers to the suppler to discuss possibilities of AM, which is not uncommon in the industry at this time. Knowing what to investigate at which stage in the process can save time and money, and make the contact with possible suppliers run smoother.

6.2.5 Project improvement potential

As with all projects there is always room for improvements. Some of the possible improvements are described in this chapter.

Using topology optimization

An area that could have been improved in the case was the use of the topology optimization. The first concepts of improvements of the BOR-elements design, that were created in the project, were based on the assumption that the BOR-element would need an inner structure to hold both its own weight but also that of the outer environment including when it would be assembled as well as vibrations etc. If the topology optimization had been performed in an even earlier stage it would have been evident to the authors that an inner structure is not necessary to have, which would have saved time, and effort which could have been spent elsewhere. This really shows the importance of basing decisions of facts, as well as the great advantage of using topology optimization in projects that include AM.

Restricted information

Due to the fact that there is some confidentiality restrictions regarding the information about the product, because of the nature of its applications, not all data was viable to the authors. A full list of demands was never presented, which means that there might be aspect that the authors were not able to take into consideration in the use of ETAM, which might have led to another answer than the one that is presented in this project. However, as the case is to illustrate how well the ETAM method works and the given information is enough for this purpose. Also, as the decision was made to only consider the BOR-element and not the rest of the assembly, there might be other aspects that are connected to the rest of the parts in the product that are not considered and might change the outcome as well.

Communication with production

In the design of the BOR-element, it was evident that communication between the production and the product development teams are of the out most importance. One aspect of this was already covered in chapter 6.2.2. Another aspect is that of the design process of the bottom surface of the BOR-element. In the simulations of the forces that the geometry would need to withstand it was clear that one prerequisite for having the optimal situation would be to ensure that the outer ring of the bottom of the BOR-element is in contact with the surface beneath it in the assembly. This was first ensured by creating a hollowed out ring in the middle of the bottom surface, in combination with a slight elevation of the hole for the screw, to make sure that the outer ring would be in contact in spite of for example possible deformations. This feature would need a support structure in the build phase, and since the bottom would need to remove support structure either way, this would not cause any extra work in the production process. When this was tested, the result was that the support structure of the feature did in fact complicate the support removal process and caused markings in the final product. Because the method of AM is new and there is still a learning process to fully understand what the limits are, it is situations like this that can occur which can drive the learning process forward.

Data for testing

When the final design of the BOR-elements was completed for the project, several prototypes were produced. There were four printed parts of each of the three investigated wall thickness designs, including one that was split into two halves for each size. There was also one element that had been after-treated through turning as a pilot project, in order to show that this was possible to increase the quality of the surface finish. When conducting tests on the BOR-elements regarding the accuracy of the weight these were the only elements that were available. Since this is a rather low sample size, no real assumptions can be made, as basing decisions on facts and not drawing conclusions based on uncertain results, is important.

6.2.5 What is the next step?

As was mentioned previously in this chapter, further testing of the function of the BOR-element should be conducted before moving on to a full-scale production. The next step for evolving the BOR-element is for mechanical designers to dimension the possible thread insert and screw. Some preparation work was performed in this master thesis for this dimensioning. To encourage the AM process by avoiding unwanted overhang the screw hole was raised by a few millimeters. This also makes the attachment less sensitive to settlement. However, investigating this further is not within the scope of the master thesis. Also, if the recommendation of integrating parts is followed, this dimensioning could become irrelevant as the BOR-element would be fastened in some other way that is not possible to predict at this time in the course of its development. This is an important dimensioning since the tests show that the areas around the screw hole is the most affected when it comes to outer forces (see chapter 5.1.11).

7. Conclusion

The two research questions that were the basis for this master thesis could be answered, and the result was as follows.

RQ1: In what way does additive manufacturing (AM) change the starting point for product development, and product redesign, in regards to possibilities and limitations?

AM changes the starting point for manufacturing in the way that it challenges the traditional way of producing. The techniques of AM are built on the basis that material is added rather than removed, which is the case of many of the traditional methods. This means that using AM requires a new way of thinking by designers, engineers and everyone involved in the manufacturing process. Not everything that can be designed can be manufactured, which means that to be able to take full advantage of the possibilities of AM the involved parties must have an understanding of what parameters define the success of a AM project. For this, adapting products to fit AM production is necessary.

- *Possibilities of AM:* AM makes production of complex shapes easier, and it allows part integration to a high extent. As several parts of different types can be produced in the same round in AM machines, and tools for machines can be produced through AM more easily, AM can be a part of increasing production efficiency. AM enables weight reduction, part and production flexibility, material efficiency as well as resource efficiency.
- *Limitations of AM*: There is a need for support structure in the build, layer thickness and resolution, geometrical and mechanical limitations, as well as imperfections and a relatively high cost. The translation between the virtual design to a format that the AM machine can work with is only one of the many things that operators working with the technique would need to learn to optimize the process.

RQ2: What are the key factors to investigate when converting a product to additive manufacturing as a production method for high technology metal products?

Six factors have been identified through literature studies, external forces, AM strategy, AM technology, supply chain, system of operations, organizational factors. These factors have been grouped and evaluated. How can these be applied to a method for product development?

To apply this to the process of converting a product for additive manufacturing as a production method these factors need to be interpreted and made more specific. A method named ETAM was created with the following steps that represents the steps in a generic adaptation process, as it has been identified in this master thesis project. ETAM enables the key factors to be a part of the conversion process.

1. *Product Analysis* – analyzing what features are vital for the function to eliminate those that are not needed in the new design for AM.
2. *Production Analysis* – Mapping the relevant AM methods, and mapping the opportunities and constraints of these methods, narrowing down to what method is the better one.
3. *Updated list of requirements* – A new combination of the demands from product and production that is free from unnecessary constraints, opens up for making full use of

the benefits with using AM.

4. *Re-design* – The product is redesigned using these demands in mind.
5. *Experiments/Simulations/Calculations* – Making sure that the part is fulfilling the set demands and if these need to be altered and put in a new list of demands.
6. *Final re-design* – This is the design of the final product when optimized for AM.
7. *Plan for manufacturing* – This step is when decisions and plans should me made regarding how the product is going to be manufactured: in which angle, the number of products per batch etc.

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Personal communication

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2. Farhad Golkar, (Arcam AB) interviewed through questioneer 2015-08-10
3. Tommy Gustavsson, email 2015-08-17
4. Sebastian Hällgren (SAAB Dynamics) interviewed by the authors 2015-10-06
5. Anders HÖÖK (SAAB EDS) interviewed by the authors 2015-10-20
6. Karolina Johansson (Lasertech) interviewed by the authors 2015-10-01
7. Sofia Målberg (SP) interviewed by the authors 2015-09-10
8. Åke Nilsson, email, 2015-07-01
9. Ronnie Petrini (SAAB EDS) interviewed by the authors 2015-11-09
10. Joakim Ålhgård (SP) interviewed by the authors 2015-09-14

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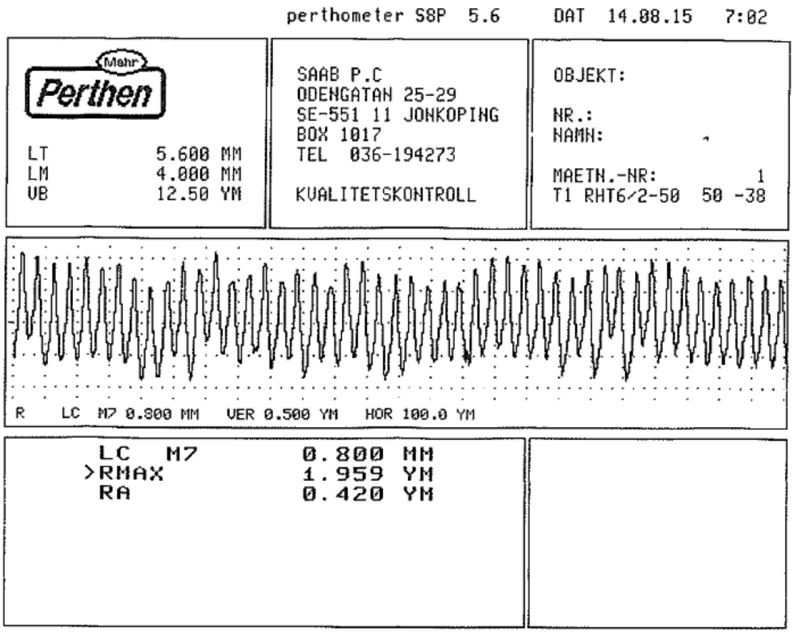
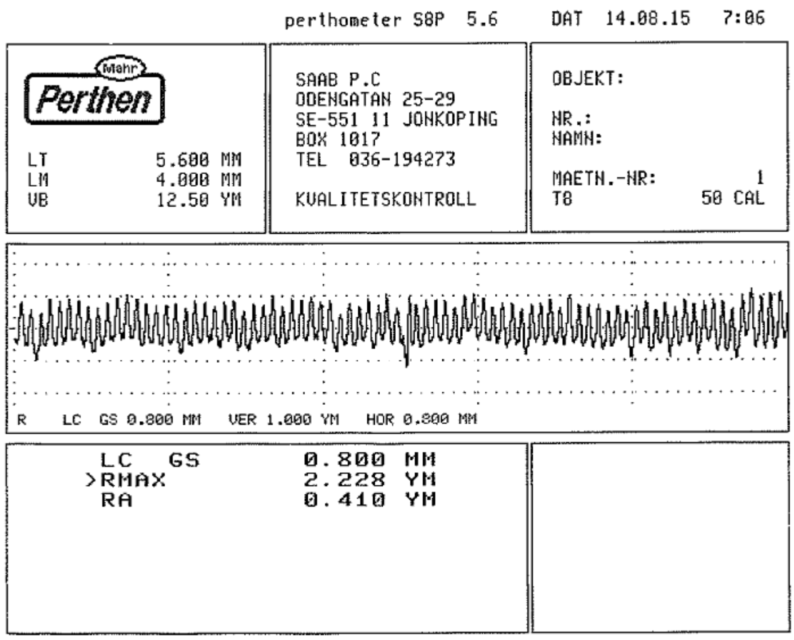
9. Appendix

Here follows the appendices of interest for this report. Summaries of all the interviews conducted during this project are included but also technical data and project findings.

Appendix A – Surface roughness measures from Husqvarna





Appendix B – Interview with Lars Emanuelsson, SAAB EDS

Lars Emanuelsson is an employee at SAAB EDS. His expertise is producibility and he functions as a link between the product development department and the production department.

Q1. Could you tell us about yourself?

I help the engineering departments with determining producibility of products that they design, and I also work in the production, with for example programming machines, running machines, and also programming of the machines for quality control.

Q2. Could you tell us about your connection to the product development process at Saab?

In general, when working with CAD software and design, there is a gap between what can be drawn in a CAD and what actually can be produced. Also, if your draw a product in a cad, and for example make the tolerances too strict, that might make the part impossible to make since no production method can make that product at that accuracy. When setting tolerances and demands, these need to be possible to meet and you must be able to repeat the result. These tolerances must also need to be controlled.

Q3. How do you think that AM could affect this process?

From what I understand regarding AM it makes it possible to produce things that could not be produced otherwise. At Saab EDS we have an AM machine for prototyping in plastics that we have people that have experience working with during the time it has been here.

When it comes to evaluating producibility it is important to have the producibility aspect in mind as early on the process as possible. That is how you will get the full picture, and not just keep on working in your own direction, regardless of if what you are designing is possible to produce or not. Considering how designs affect the difficulty level of the production, as well as considering the price is an important aspect.

If AM would become an option I think that, since AM is so different from traditional production methods, you would almost need to have two separate tracks when considering your design and production choices. And if a product is already designed for another production method, like turning, it would need to be adapted in order to fit AM, to make it worthwhile to actually choose AM instead of the original production method. I could imagine that there are examples of products becoming much more expensive if they are produced through AM, making them not at all suitable for the method, as they could be produced much more easily by using traditional methods like perhaps milling. It can take a very long time to print sometimes. There must be a balance between the pros and cons of using AM as with any method. For example, if you can make something very thin, is it worth an extra cost etc.

Even though you cannot know the exact price at the beginning of a project, you can calculate so that you at least get an idea of what it would cost, to compare.

The thing is that you can design almost anything in a CAD, not all of which can be produced, through any method. AM have more possibilities in what can be produces, in terms of impossible shapes and so on. For traditional methods it is more straightforward when determining producibility for parts as the tools only enable so much. With AM you can do a lot more, and this means learning a new way of thinking. If AM is implemented, you need to learn how to determine how the parameters affect producibility for this specific method. It is so new so not a lot of people have that knowledge yet.

Q4. In your experience, what are the main things to consider when using AM as a production method?

I have seen, in the prototype production here at Saab EDS, one of the main things that should be considered is the scaling of a product. It is important to know what the machine is actually able to print. For example this could be connected to how small you can make objects. If you have a larger part in the CAD and you just scale it down without considering the abilities of the AM machine the parts that end up being to thin to print will disappear.

The process of printing can be time consuming, especially when printing solids. The production time can be shortened by decreasing the material use. By doing so you can reduce the material cost as well.

Q5. Over to ETAM, what are your comments about the ETAM method?

Regarding C1, it is good that the product and production is in parallel to each other, as this allows producibility to be a part of the design process as early as possible. As I mentioned, you can spend so much time on drawing but in the end not being able to actually produce it. This step enables that you get the full picture right away, and that everyone gets to contribute to making the product better.

Regarding C2, and the iterative process with the updated list of requirements, redesigning, experiments, and creating a final design, is what we have been looking for. It is good to perform simulations, but it is of value to test on physical products as well. Since it is such a flexible method, making prototypes is very easy too. It is good that you have included this iterative process, and that ETAM gives you a chance to go back and review if you have fulfilled what you wanted to do before preceding to the next step.

Appendix C – Questionnaire to Farhad Golkar

The following is the answers to a questionnaire sent by the authors which was answered by an expert in AM at Arcam AB. Arcam AB is a world leading innovator within the field of AM, and the information provided gives insight into the current state of AM as well as giving a hint into what the future of AM could be.

Demographic questions:

D1: What is your profession/working title?

Farhad Golkar, Process & Material Development. Ph.D.

D2: How many years of experience from working with AM technology do you have?

3 years

Question 1: Technical advantages

The first three questions of the questionnaire will cover the technical possibilities of AM of metals.

Q1a: What are the current technical *advantages* for AM of metals in comparison to traditional production methods? (E.g materials, tolerances, angles, production time)

<u>Advantages of the Electron Beam Melting technology (EBM):</u>

- Freedom in design (Complex structures can be produced in one step. Can combine porous structures and solid structures in the same manufacturing step).
- High productivity (The higher complexity of a part the more to gain compared to traditional methods)
- Tool-less manufacturing (No down time due to tool changes. System can handle many different designs. No tool changes need to be made between different products).
- Shorter lead times (From CAD model to final product).
- High power available (up to 3000 W) allows melting of an extensive range of materials (the melting point is up to 3400°C).
- The EBM process is performed in a vacuum chamber i.e. eliminates impurities and yields excellent material properties.
- High process temperature results in low residual stress in the final part and there is no need for heat treatment.

Q1b: How do you think that these *advantages* affect the use of RM of metals?

With no limitation in design of a part it opens up possibilities to reduce the number of components in an assembly (e.g. combine two parts into one). A shorter lead-time allows for faster and more iterations of part design during a development stage.

Q1c: What do you think are the technical *advantages* for AM of metals in the *near* future (1-5 years)?

Increased productivity. Larger components can be built. Post machining process not needed for surface finish. More customized microstructure in a component. Increase of Beam Power

Q1d: What do you think are the technical *advantages* for AM of metals in the *more distant* future (> 5 years)?

Larger extent of customization. Build with materials that are not possible with today's techniques. Not only production but also reparation of metal components.

Question 2: Technical limitations

The following questions are concerning the limitations of AM of metals.

Q2a: What are the current technical *limitations* for AM of metals? (E.g materials, tolerances, angles, production time)

The EBM technology requires pre-alloyed materials in powder form. Post machining is needed to obtain high surface finish. Still an advanced technology it is not "plug-and-play" yet.

Q2b: How do you think that these *limitations* affect the use of RM?

Being limited to pre-alloyed powder can limit the application area. Since EBM is new compared to say well known casting it can be a threshold to accept the technology.

Q2c: What do you think are the technical *limitations* for AM of metals in the *near* future (1-5 years)?

Still too advanced technology to replace existing technologies (such as casting) for production. Control of the electron spot will be more difficult with increasing beam power. New material alloys with higher demands than the technology can handle.

Q2d: What do you think are the technical *limitations* for AM of metals in the *more distant* future (> 5 years)?

New material alloys with higher demands than the technology can handle.

Question 3: Sectors using AM

These questions are regarding the current and future sectors that have implemented RM.

Q3a: What are the current interesting sectors for AM of metals?

Medical. Aerospace (aviation)

Q3b: In what sector do you think AM of metals will be expanding in the *near* future (1-5 years)?

Medical. Aerospace (aviation)

Q3c: In what sector do you think AM of metals will be expanding in the *more distant* future (> 5 years)?

Automobile. Tooling. Aerospace (rockets, satellites)

Q4: To what extent do you think that the company experience of rapid prototyping will affect the use of RM?

With more experience and knowledge in prototyping will make the transition from prototyping to the RM stage easier and faster.

Q5: What is your impression of the general attitude towards AM is?

Exiting technology with great potential but still not mature enough.

Appendix D – Interview with Sebastian Hällgren, SAAB Dynamics

Sebastian Hällgren works at SAAB Dynamics (SBD) and is currently an industrial post-graduate with a focus on AM. He was partly involved in the OPTIPAM project and has knowledge about SAAB's products and was therefore interviewed.

Q1. Please tell us a bit about yourself. What is your background and what connection do you have to AM?

I have worked at Saab Dynamics (SBD) since 1997. The first years I worked with mechanical design, then seven years as a section manager. After that I worked with mechanical design again for one year and before I started doing this post-graduate involving AM.

Q2. Can you please tell us a bit about your project? How are you related to OPTIPAM?

My assignment in this is to, for SBD's sake; map the designing guidelines for AM. OPTIPAM aims to start research in 3D printing in Sweden, create a competitive edge for Swedish industry in niched manufacturing methods. Therefore, both the academic world and the industry are involved in the project.

Many scientists tend to look through a microscope and say; ”This is how it is. We have alpha structure here and grain boundaries look like this”. Personally I do not think that is interesting but there are a lot of material interested researchers and therefore a lot has been done within this field on many materials. Less research has been done on aluminum used for 3D printing. That is because aluminum is cheap to cut in and to compare that to other manufacturing methods is hard. Generally speaking, if you have a few, use milling if it is possible. Or use molding if that suits better.

But if you look at titanium it is much more difficult to cut in and relatively fast printed. Titanium is 50 % faster to print than aluminum but aluminum is six times easier to cut in. And if you add these differences there is a large difference in the suitability for each material. If you need titanium it can be a value in printing even though the volume size is low and if the shape and geometries can be motivated through a customer perspective.

A good example is a satellite. If you are going to make one or two satellites you are well updated about the forces that it has to stand, since you have to when it is satellites. You never take chances when it comes to space. If I then use topology to iterate the optimum design and then print it in titanium I know that it is financially sustainable since I'm only going to make one and titanium is difficult to manufacture in other ways.

Because the price might have been 30000SEK per printed part when you have an alternative manufacturing method that offers the same product for 5000SEK. If you are going to buy one million of these products the amount of savings are often worth investing in a mechanical designer who can solve the problem. Another aspect is also to involve the customer value when it comes to weight reduction. How many customers are willing to pay the extra for 10 grams weight reduction?

There is an area for when AM is worth using in order to make it a competitive advantage. It is mainly when something cannot be manufactured in any other way, which on the other hand can be seen as a failure for the mechanical engineer. It is his or her responsibility to design something that is possible to manufacture.

When you in CAD use “extrude” or “revolve” you simple simulate milling and turning. If you then start doing “sweeps” or double-curved features you have to find a value for that specific design and if you then can realize it with AM you are onto something!

Q3. Earlier you have talked about tolerance accuracy for AM. Can you elaborate that?

It is important to get the proper education and understand how the machine functions. Your first article that you produce will probably not be that good in comparison to the other you make once you’ve learned how to handle the machine. For AM it is probably easier than for milling that involves more manual work. However, if you use the machine and the actual manufacturing cost is 50 000 SEK then you have to add 2 days of delay and failed manufacturing due to iteration.

Many designers and customers think that using AM is easier than what it is and their demands are unrealistic. For example they do not know that some materials are very difficult to print and therefore the building time is longer.

Is it due to material, shape and volume size that the suitability for AM is classified?

There are limits to the accuracy of the parts that are produced, you have to evaluate if it worth the cost of making it producible. It could be better to accept these limitations, and work with them. After-treatment is both costly and time consuming, but mostly costly.

Q4. What do you think are the possibilities and limitations with AM as a manufacturing method?

The price of an AM produced product is to more than 50 percent determined by the time it takes to print in expensive machines. Therefore I think that in the near future AM will mostly be used for high cost, high value details, often in exclusive material. I think you will focus on increasing the value of the function rather than reducing production cost. If you want to reduce the price when designing for high volume manufacturing, it is important to consider the value for the customer. If the customer requires a low mass, a topology optimization could be a way of realizing this.

I think that it is difficult to reduce the price. Perhaps if you succeed to integrate parts with each other because then you can remove the complexity of assembling. The engineering cost is the largest cost; you want a low engineering cost and high customer value.

If it is single batch articles the manual work has to be decreased as much as possible. For teeth it has been solved by for example scanning the teeth, converting it into the machine and print it as an automatic process. By that the cost is maybe 10 000 SEK instead of one million.

Q5. What do you think about the general knowledge of AM at Swedish companies?

I do not think that it is particularly high, especially not for metals, but I don't have any data on how companies in Sweden view AM. The difference between research and product driven development is that you learn what you need to know because you are developing the product, not AM.

Do you have any questions or comments that you would like to share?

No, I believe that if SAAB EDS focus on reducing the weight it is possible to quick get an insight into how AM works. However, it is the complex geometries that are AM's strength.

Appendix E – Interview with Anders Höök

Anders Höök is an antenna expert working at SAAB EDS. He has a valuable insight to the BOR-element but also a profound knowledge about the theory behind antennas. Therefore he was interviewed in the project.

Q1: Please, tell us a bit about yourself and your background.

I think it is enough to say that I am an engineer within physics engineering. After that I did a PhD within electromagnetic field theory, started as plasma physicist and ended up working with non-linear fiber optics. With that said I work with physics, as it was known during the 19th century.

Here at SAAB EDS I work as an antenna specialist. Since the BOR-element is a part of an antenna I am interested in it along with other antennas.

We want to assure that none of the essential features of the BOR-element are removed.

Q2: What features in the BOR-elements are important for the function of it?

From the beginning Holter (Editors remark: Holter, 2007) designed the BOR-element and we have done some modifications. Sometimes we change the frequency span or iterate in some other way for it to fit with different products. And that will affect the function of course. But that is so called electrical construction where everything is assumed to function according to theory. For example, if you design an antenna element of the BOR-type, you would assume that these tips are perfect electrical conductors. Different metals have different electrical conductivity, and in this case it is an aspect connected to the material.

Then it is also like we have discussed previously. It could also depend on the surface roughness. The BOR-elements in question are operating on a slightly lower frequency, making it relatively tolerant to surface roughness. A colleague is working on a report about PCB membered RF-lines where the copper webs are everything but smooth, and these have losses, which are visible in higher frequencies, 12-18 GHz. This is where this type of surface roughness losses manifests themselves.

Then there are also other aspects. These (editors remark: BOR-elements) are supposed to be mounted onto a surface where the assumption is made that they are in perfect electrical contact. This is not always the case, in reality, and the contact areas that are formed electrically can vary a lot between two elements. The contact area is important, especially in the outer part of the bottom surface.

Also this is good for stability, to ensure that it does not just have contact with the screw. Other things can factor in as well such as corrosion against the underlay of they are of different material with different potential.

For the BOR-element we have chosen a material that is an alloy of aluminum. Aluminum is not very hard and perhaps not suitable for screwing into, so the solution could be to use a thread insert. This tread insert is made of steel.

Q3: Would this be a problem in terms if corrosion?

Yes, I'm “allergic” towards not analyzing the aspects before making this type of decisions. A percentage of decisions not thoroughly thought over will conduct to a shortening of the product life. In this case corrosion could conduct to a deterioration of the ability to conduct signals in a later stage. So this is an aspect to consider as well, and also oxidation, if they are exposed to air under a longer period of time.

In the article by Holter (2007), Holter presents a list of the most important demands on the antenna unit. We would like to go through these with you.

Q4: Which of these are relevant in our case?

The first thing to notice is that these BOR-elements are of another size compared to the ones you are looking at in your project. Your BOR-elements are intended to operate at considerably lower frequencies than Holter’s version, which includes 12 to 18 GHz and thus makes them more sensible to surface roughness.

The conical scan volume is a matter of design and will probably not affect the aspects that are included in your project, assuming that we solve the possible issue with material compatibility and securing the electrical contact area.

Double polarization and grating-free operation is inherited in the construction. Grating lobes occur when your elements are too separated. Then you can get unintended extra lobes in different directions. This is an aspect, which is related to the design, and is already solved in this case.

Standing wave ratio is also a main matter of design. If you adapt to the geometrical design this should not be an issue. Again, with the assumption that we do not have any increase in resistivity, because of either a poor interface between BOR-element and underlay, or oxide formation.

The antenna will need to be able to both transmit and receive signals. To be able to use these functions over a long distance, you will need to enhance the performance of the antenna by dimensioning it to a certain size. This enhancement is connected to the number of elements that is in the antenna. A high-performance EW-antenna, regardless of its system band would have around 200 elements. This is a generic number that you can use.

Such antennas can be considered for tracked vehicles, stationary installations, ships and aircraft.

As we have mentioned previously, we asked Andreas Wikström to do some calculations on how the surface roughness affected the signal strength, to see if there would be any damping of the signal for the 3D-printed BOR-elements. We understood that the model that is used for this assumes that the material is copper, not aluminum, and that it is of a different structure in the material.

Q5: How does this affect the reliability of the results?

The Huray model that Anderas Wikstöm used is primarily intended for gold plated copper. If you look at a surface like that you could see that the gold is arranged like balls on the surface. It almost looks like a ball pool at IKEA. Huray performed a thorough analysis of how current that is transported in a surface like that is dampened by the structure. The way a current is dampened by a surface like that will almost be a worst-case scenario. The surface finish of your 3D printed BOR-element provides better possibilities for leading current than the Huray-model. This means that the calculation Andreas Wikström did is a conservative one. He found a maximal dampening for a certain size of the balls corresponding to the Ra-value you gave him. His conclusion was that the printed surface would be sufficient. Looking into if the surface could be after-treated with turning, like you suggest, would be interesting for these higher frequencies.

Q6: What are the boundary conditions for this Huray analysis?

The Ra-value is a measure of the roughness of the surface, which is related to the ball size in the model, so this is the parameter that is changed primarily, but you can add other things as well. For example, the way the balls are placed does not have to be completely smooth. It is possible to really dig in to this but I think that the model that is used is a robust approximation, and that saying that the Ra-value can be taken as the ball size, which was what Andreas Wikström used in his calculations, is adequate.

The results are especially reliable because you have a much finer surface, so the results are even more positive.

Q7: Could you tell us about the skin effect?

Imagine a power line: a wire with a certain diameter. There is an electrical current going through it, with the purpose of transporting electricity from producer to consumer. The static resistance is proportional to the length of the wire, and inversely proportional to the area of the cross section of the wire. This means that there is less resistance when increasing the area and more resistance if you make the wire longer.

The skin depth manifests itself at high enough frequencies. In the power line example, the current ultimately flows in a thin layer at the surface, the skin. As a result, the resistance increases. In the situation with the BOR-element we are using alternating current, so it is really just the outer surface of the BOR-element, which is active for sending and receiving signals. If this thin layer is smooth and has a low surface roughness the signals can travel without hindrance, but if the surface is not smooth the electrons are forced on a longer route, which increases the resistance further. This adds extra losses, which was what Andreas Wikström looked into. The Huray model takes the ratio between the skin depth, and the surface roughness into consideration. If the skin depth exceeds the surface roughness the current can pass below the irregularities in the surface. However, if the frequency is increased to typically 12 GHz, the skin depth with be so thin that the current is forced to follow these dips in the surface which increases the losses, because then the current is affected by the surface roughness. There is an equation for this.

Q8: Could the height of the BOR-element have an impact on the function?

In this case I don't think it matters, since the height differences is less than the tolerance.

Q9: Could the surface roughness affect the noise level in the signal?

Noise in the signal is that the signal becomes a sum of frequencies that are not correlated with each other. Since the element only works with a set frequency I don't see how new frequencies would be created like that. Possibly if the signal needs to travel through an area where there is oxidation a diode effect could occur. I would say that it is theoretically possible, but in reality not relevant.

Appendix F – Interview and mail conversation with Karolina Johansson

In connection to the case study of the BOR-element, Karolina Johansson who is working at Lasertech was contacted. Johansson has experience in the AM method and could give important information and feedback to the authors regarding what the possibilities of AM are. The contact and interviews consisted of both email correspondence as well as in person, and took place during several occasions.

Interviewee: Karolina Johansson – Lasertech 24th of June 2015

We are investigating the possibilities for producing the larger version of the BOR-element using AM in order to be able to survive the environment in its lifespan.

When it comes to the inner structure of the new design for the BOR-element, there are several alternatives, for example, creating round bubble-like inclusions of air in the structure, making the outside a shell only supported internally by latticework, or a honeycomb structure.

Q1: Are structures like this possible, in terms of producibility, when using AM?

There are some geometrical limitations that should be taken into consideration. One is the angles of the parts produced that might make additional support structure connected to the production process itself necessary, a second aspect is the removal of excess metal powder, and then there is the question of quality being affected by the translation of the step-file containing the design that the AM-machine uses as a blue print when printing.

A printed internal latticework or honeycomb structure could be an option but both thickness and angles play a role here. The round bubble-like inclusions will not be possible to make hollow unless there are some kind of holes or pathways included in the design so that material can be drained from them.

Q2: Why do we need additional support structure for some angles in the design?

The machines that are used for AM for metals often cannot handle overhang, meaning angles in the structure that are less than 30 degrees from the horizontal plane. If the design includes angles like this, an extra lattice support structure is needed. The reason for this is that the newly printed material does not have anything to "stick to", which can create a bend or rough surface. Another problem with overhang is that, for example in the SLS-method, the laser beam affects about three layers down into the powder bed bellow. This can create a beardlike structure from under the overhang.

Q3: Is it possible to avoid these support structures?

By reducing the number of these kinds of angles in the features of the design, the need for support structure is also reduced.

But, either way, some kind of support structure is usually needed when using AM for metals, and prepared before the AM process can begin. This support structure is made out of metal, and functions as a physical support which keeps the work piece in place as it is being printed, as well as being a thermal leader.

Q4: How does the step-file translation affect the outcome?

As you might have noticed, some of the 3D-printed parts that are on display in the office were meant to be curved, but instead had step-like features. This is due to the translation between the different formats. The step-file translation is sometimes not ‘good enough’, which results in deformations like this. This is something to consider.

Being able to withstand pressure differences could be one of the demands that are put on the BOR-element. We have an idea that we do not want possible pressure differences between the outside and the inside of the BOR-element to cause stresses in the material. Therefore we have discussed creating holes in the structure, minimizing the pressure differences, if needed.

Q5: Is it possible to create holes in the structure to minimize the risk of pressure differences if the BOR-element would be subject to pressure differences in its lifespan?

That would be possible. The question is where you would place these holes, as the angles are important when it comes to AM. The accuracy of the holes can depend on this. Another aspect of this is that holes in the structure could serve another purpose, which is getting the excess metal powder out of the part after the AM production.

As the electrical conductivity is an important demand on the BOR-element, the goal is that the new BOR-element will have the same characteristics in this aspect as the existing one. When comparing AM to the current method of production, turning, it is clear that at present the smoothest surface finish of AM produced metal parts seems to be rougher. This could possibly interfere with the electrical properties.

Q6: Could we make the surface finish smoother by for example, making the layers for each swipe of new metal powder thinner?

Making the layers thinner is possible, however, it’s not something that would be recommended, and I’m not sure it would help. In order to do this we would need to unlock the parameters of the machine. This means an additional ‘unlocking’-cost to the machine provider, which can be quite high at the moment, and the machine provider will often not guarantee the quality of the parts produced after unlocking the parameters.

Q7: Is it possible to fit even more BOR-elements in, if half of them were upside-down?

Yes, that could perhaps be a possibility, however, you need to consider the angles, and how that could affect the surface of the upside-down parts.

Interviewee: Karolina Johansson - Lasertech 30th of June 2015

We are interested in exploring the possibility of manufacturing the BOR-element, which was discussed at our previous meeting, through 3D-printing, (or AM). The goal is to change the design so that it keeps the outer geometry, but instead of a solid, we want to create a shell like structure with a supporting inner structure. We are looking into how this inner geometry could look, to reduce the weight of the product while keeping the same function as before, either by using spokes, or a net-structure.

Q1: Do you have any input on what an internal structure like this could look like to improve the produce ability, and general input regarding minimizing the need for lattice support during production?

From a producibility perspective, the best idea is to make cavities straight up, vertically, into the BOR-element, and save an outer shell with a minimum thickness of 2mm (if using the specific EOS-machine that was discussed during our last meeting). Between these cavities there should be a distance of 1,5mm. What an optimal diameter of these cavities should be, i can't provide an answer for.

We are interested in looking into the possibility of keeping the same surface finish as the current concept, which is produced through a turning process, mostly on the outer surface of the BOR-element.

Q2: What kind of post-production treatments does Lasertech currently have available, or would recommend, to achieve this kind of accuracy?

Lasertech can provide a number of different after treatments or post production treatments, including turning. If, however, the tolerances of the surface finish are not as narrow, an alternative that I would recommend is tumbling. This will not keep the tip of the BOR-element sharp, though.

Q3: What forces stresses does that post production treatment put on the BOR-element, meaning, what forces does the structure need to be able to withstand without causing deformation of weakening the structure?

I can't give you any exact numbers when it comes to the forces during a potential turning process, but I suspect that they would be negligible.

Q4: How much material could need to be added to the AM produced part to fit a post-production treatment, for example how much wall thickness would need to be added to the BOR-element, which would then be removed in a turning process?

If the surface finish needs to be as "good" as it would be if it was produced by the production method turning, you would need to add 0,2mm to the wall thickness. You could also need to add an additional 'floor' to the BOR-element, to be able to fasten the work piece in the turning machine. This would consist of an extension of the bottom of the BOR-element, of 10mm.

Currently, the BOR-element is fixated to the rest of the assembly by one screw for each element. This design solution is something that we are interested in keeping, in the new AM-adjusted design of the BOR-element.

Q5: Is it possible to make threads in the original design of the AM machines that Lasertech have available, while keeping the same tolerances as we have in the original version?

It is possible to make threads in the original design when using AM, for example the plastic parts that we showed you at the last meeting. For aluminum, though, it is not something that would be recommended, not if you want to keep the same tolerances.

Q6: In what stage of the process would you recommend that threads are added, or would you recommend using a thread insert?

The threads should be added after the AM process. Aluminum is relatively soft.

We want to change the design of the BOR-element, from a solid to a shell with an internal support structure. As we need to take into consideration that the unused metal powder within the geometry needs to be removed after the AM process, we want to add a possibility for this in the design by adding holes somewhere on the shell, like we talked about.

Q7: What diameter do these holes need to be to allow for the metal powder to come out, and do you have any general guidelines for this?

The holes do not need to be straight, but rather follow the outer layer of the surface of the BOR-element. This is an illustration of what I mean, (see Figure 1).

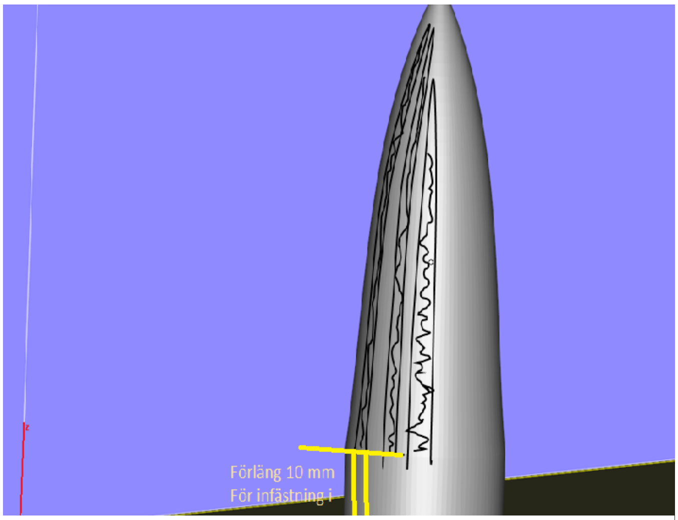


Figure 1 - Visualization, by representative from Lasertech AB, of the BOR-element including the extra material on the bottom, marked with yellow, which is needed for turning if this is needed as a post-production process to ensure the surface finish meets require

Interviewee: Karolina Johansson - Lasertech 17th of August 2015

Designs for the BOR-element that are more adapted to AM, but there are still some details where we need additional information, regarding the geometrical limitations that are connected to AM production.

The concept that we have put forward is one that has more than one hole in the bottom of the shell of the BOR-element, in order to get the unused metal powder form the production process out, in a practical way. The holes that we have experimented with are 1mm in diameter, and we want to keep the holes small in order to minimize stress.

Q1: Do you have any guidelines on any recommended diameter of holes in parts created by AM?

Regarding holes in the bottom of the part, they would need to be slightly larger than 1mm in diameter. At Lasertech, we do not have any set guidelines regarding this, however, in my experience, holes with a diameter of at least 1,5mm to 2mm makes things easier. It is preferable to be able to blow compressed air into one hole and have the excess metal powder from inside the work piece, comes out the other.

One guideline that we interpreted during or first meeting was that when it comes to setting the geometry of a part that will be produced by AM seems to be that having rounded edges was to be preferred.

Q2: Are there any specific radiuses, both horizontally and vertically that would facilitate the AM production, or make the quality of the surfaces 'better'?

During the first meeting we meant that under a perpendicular overhang, an extra support structure is needed in the production process. However, if the design instead had a radius, we could avoid using this extra support. Completely vertical surfaces get the best quality.

When it comes to the support structure, we were under the impression that it is added before the printing procedure begins, to hold the work piece in place, and to lead the excess heat away from the work piece.

Q3: When using AM, does support structure need to be added even though there is no overhang in the geometry?

The support structure is not added before the printing process. It is, in fact, printed at the same time as the work piece. In one way or another, the support structure is always needed, even just to elevate the work piece so that it is possible to remove it from the AM machine (by using a saw or spark erosion).

The added support structure then needs to be removed, as an extra step in the production process.

Q4: Is this correctly interpreted, and in that case how does that removal process work?

That is correct. At Lasertech we currently remove the support structure manually, with for example pliers.

For the SLS method we have found that sometimes the work piece is first printed and then sandblasted. When analyzing the data of the surface finish produced when using AM, we have found that the surface finish is 'better' before the sandblast procedure for the metal that our product will consist of.

Q5: Is this correct, and in that case, why is sandblasting used?

It is correct that sand blasting is used; however, we do not feel that the surface finish is 'worse' after this procedure.

Appendix G – Interview with Sofia Målberg, SP

INTRO

Q1. Could you tell us about yourself and about the project OPTIPAM?

I am the head project manager for the project OPTIPAM, which aims to strengthen the competitiveness of the Swedish industry, through increasing the knowhow and use of additive manufacturing as a production method. I also have a technical coordinator and specialist for the OPTIPAM-project (Joakim Åhlgård) who has the technical competence since he has a doctorate degree in the subject of additive manufacturing. That's why it would be beneficial to also interview him regarding some of the technical details as he has a deeper knowledge on the subject. My own background is in material science.

The OPTIPAM project, which stared in December of last year (2014) but actually really begun in January this year (2015), and has been in progress for the past nine months. The project is financed by Vinnova and has a budget of almost eleven million, for two years. The purpose of the project is to face the challenges of additive manufacturing for the companies that are involved in the project.

The companies that are involved in the project view additive manufacturing as something that is making its way into the market and into their specific field, and they want to understand how they can use AM to increase their competitiveness. They want to achieve this through shortening lead times and improve their processes.

The companies are looking for design, quality control and weight reduction. The demand for weight reduction is mainly connected to the aerospace industry.

AM is often used for making prototypes, but then mainly for making smaller parts. The question is what companies need to be able to dare taking the step to introduce AM in their production line. I don't think that AM will ever replace the traditional production methods. AM will instead be a complement, since the method has many advantages, but also many limitations. That is why it will never completely be a replacement, and some products will always be more suitable to be produced by traditional production methods.

The question that we are working on the most is where the limit, between when it is more economical to use traditional methods and when it is more economical to use AM, is. That limit is very hard to define, and that is why we are trying to define, for the companies in the project respectively, where their limit is. The limit does not have to be the same for everyone. It is also important to clarify where that limit is for the respective design engineers and designers at the companies, so that they can decide when it is suitable to have AM as an option as a production method. Where that limit is can, among other aspects, be how complex the geometries the product has as well as the extent of which there is a possibility of integrating parts.

We have a person who is studying for a doctorate in the project, who is connected to SAAB Dynamics, and is located at Örebro University. His job is to investigate which of the thousands of products in the Dynamics product catalog could be suitable for being manufactured through AM.

Is this the same collaboration in which the company Lasertech is involved?

Lasertech is connected to TTC and have an EOS metal machine and an EOS plastics machine. An order for an Arcam machine will be placed shortly, last I heard. In this project the focus is mainly on AM for metals. This is because Joakim has a doctorate in metal (AM) and has been able to put a lot of focus on the technique Arcam uses. You can ask him all questions regarding Arcam's technique.

Q2. In the description of the OPTIPAM project, 'the third industrial revolution' is mentioned. What does 'the third industrial revolution' mean to you?
That is a rather popular scientific expression that was used in the application for this project. As I mentioned, I don't think that AM will revolutionize everything, because for example there is no reason why you would 3D print trash cans. In that case it is much better to use injection molding. It must be financially and practically justifiable to use AM. The details should be complex enough and it could be an on-demand production etc. There is no point in printing a detail using AM only because you can. There are many questions like this that we work with in this consortium, in this project.

Q3. As with other production methods, AM has both new opportunities and limitations. What do you consider opportunities and limitations for AM? Are some of these more important to take into account than others?
The possibility of weight reduction is something that is especially interesting for the aerospace industry. There is a possibility of having the same performance at only a tenth of the weight. There are enormous possibilities, especially with titanium. Titanium is an extremely expensive material, and usually these products are produced using turning, where approximately nine tenths of the material is removed to create the relevant detail. This means that there is an enormous waste of material. As titanium is such an expensive material, there is a lot to gain from using AM, since it provides the possibility of only using the material that is needed.

The limitations often come from that there is a common misinterpretation that AM can solve all problems. There are still aspects that need to be taken into consideration. For example the surface-finish, but also the issue of variation between the first of the produced products and the hundredth, as well as how well the drawing matches the physical product. These are the things that this project aims to clarify. This is something that SP works with, and there are limitations, as there is with all methods. When these limitations are mapped this can give the framework that one have to relate to. These are the frameworks that need to be created for the companies. It is important to find which parameters the companies need to stay within, for it to be relevant to produce through using AM.

For smaller, simpler machines, it is possible to basically push a button and get the wanted geometry directly from the CAD-model, but when looking at the larger machines, all the other hundreds of parameters need to be taken into account. However, there is potential to do a lot of good things with AM if you use the method in the right way.

Q4. How do the possibilities and limitations differ between different AM methods, (e.g. SLS and EBM)?
This is a question that our technical coordinator and specialist for the OPTIPAM-project, Joakim Åhlgård, will be able to give a more in depth answer to.

Q5. In the OPTIPAM project you touch upon the subject of 'Design for AM'. This is something that could border our (master thesis) project. What does the work you do in this area look?
A big part of this project and this whole program is to spread the knowledge of what this project does to others who have in interest in it, like for example SMEs etc. We have an entire work package which has the purpose of spreading the knowledge and the idea is that it will start during the year 2016, when we have started showing results and what we plan to do is to organize workshops for design engineers and designers at the companies. So, the companies can send their design engineers to a day course, to understand how it works. The people that arrange these courses, in our case, is Mittuniversitetet who have worked with these points for a long time, ever since 2001. Lars-Erik Rännar is very interested in education, both for students and also by companies design engineers, so it is basically he who takes care of the regular business.

Q6. You also mention the development of nondestructive testing in the OPTIPAM project. Could you elaborate on this?
This includes several aspects. It is possible to look for, inclusion defects and other types of defects, and after the testing is done you can use the produces as you do not need to break it during the testing. This could be a method for the companies to test, because other types of companies check their products when on the production line, and this is something that is similar to this, which could be used here too. Also, not breaking the product to be able to test it is quite practical, and economical. So this is something that we are looking into. The interest is mainly coming from Saab Dynamics who are pushing this investigation forward; however, the other companies that are involved are also interested in this.

Appendix H – Interview with Ronnie Petrini, SAAB EDS

Ronnie Petrini works as a section manager at SAAB EDS and is familiar with the product development processes. Because of this his thoughts about ETAM were important.

Q1. In what way are you working with processes at SAAB EDS?
We are working firstly with the market strategy, and then when the set steps have been reached the process goes down on system level, and finally subsystems. We have processes for basically everything which allows a structured way of working. This makes sure that the strategies at SAAB EDS are in alignment.

Q2. In what way are you working with processes at the mechanics department at SAAB EDS?
We have processes that are connected and accessible via our intranet. I think that we are good in working with them and also adjusting them to each project.

Q3. What does the development of processes at SAAB EDS?
At the start of each project, a target is set, which is something that should be worked towards achieving throughout the process. The first step is the decision point to start review, concept, DR, physical design, DR, design test, DR, finish. This is a loop.

Q4. You have been presented with a description of the ETAM method. What is your opinion regarding the sequencing of the steps in the method?
The order of the steps is ”right” and defiantly fits with the models that we have here at SAAB.

Q5. What is your opinion of each of the process steps?
In the process at SAAB we have a process way of thinking that includes a step of both considering the demands form the company which includes the production needs, as well as the product demands, in which your similar part in ETAM would fit right in.
One thing that ETAM could really add to our processes is the focus on experiments which includes simulation, calculations and experiments. Putting more focus could encourage the staff to be more creative in their work and try new things regarding solutions for our products. This aspect could be incorporated in our business and could be something that we could benefit from in terms of increasing the level of innovation and creative thinking. You must be allowed to fail, in order to dare to try new things.

Q6. Do you have any questions, viewpoints, or input that you would like to share, on this subject?
The process fits out processes that we are supposed to follow. With all processes there is of course a level of how these processes are followed.

Appendix I – Interview with Andreas Wikström

The meeting was called to discuss the BOR-element for the case study conducted by the thesis authors. Andreas Wikström at SAAB EDS was contacted due to his practical knowledge regarding the BOR-element and his knowledge in simulation of the effects of surface roughness on transmission lines on the integrity of the signal.

Meeting with Andreas Wikström 10 aug 2015

To follow the method that we are creating connected to this master thesis, one of the very first steps in the part-redesign to fit AM as a production method, is to identify the list of demands of the product. This list of demands should be connected only to the specific functions of the part, meaning, no features that are connected to for example previous production processes should be kept in this selective process. Therefor it is important to identify the specific demands that the BOR-element needs to fulfil.

In the CAD-model of the BOR-element, there is one main concern, which is the fact that there are two additional vertical cavities in the design. The purpose of these two cavities is unknown, but knowing if they have an intended function is of importance as removing these would help in the redesign. Only the design features that are vital for the function of the BOR-element are kept.

Q1: What is the purpose of these two cavities, and are they necessary for the function of the BOR-element?

I don't think that these cavities serve any important purpose. Possibly, they could be connected to the rest of the assembly, in order to 'be on the safe side' when it comes to avoiding direct contact with certain parts underneath the BOR-element, in the assembly. For that purpose, it is not necessary to keep the cavities the way they are in the original prototype.

The design of the rest of the assembly already includes this kind of separation between the BOR-element. Then the possible function of the cavities could perhaps be seen as an unnecessary precaution.

Q2: If that is the case, is it possible to remove the cavities completely?

Yes, that would probably be possible.

The functions need to be matched with the abilities of the AM method. One aspect that needs to be evaluated is the effects that the surface roughness of the AM produced parts have on loss in conductivity. The scale of this possible loss in conductivity will be a part of determining if additional after-treatment is needed, post production.

Q3: How do you think that the surface roughness affects the conductivity?

This is something that I could do some simulations on, and get back to you with the results.

Andreas Wikström was then provided with the necessary boundary conditions for these loss calculations.

<u>Meeting with Andreas Wikström 25 Aug 2015</u>

Q1: Were there any difficulties when conducting the calculations on the effects of the surface roughness on the conductive properties of the BOR-element?

There was some difficulty in adapting the computer software to the specific situation as the simulations are constructed on the premises that the material in question is electrode deposited copper, and not the aluminum composition that was asked for. This creates an aspect of uncertainty that needs to be taken into consideration. The properties of copper verses the properties of the material of the product may also differ. Then there is the aspect of the exact structure of the material. The material properties of an electrode deposited surface may differ from one created through AM in other ways than just surface roughness, which adds another level of uncertainty. This also needs to be mentioned and taken into consideration.

Q2: Based on the calculations, should the surface roughness created through AM affect the conductivity of the BOR-element?

According to the calculations made with the given input, the losses that are connected to the BOR-element being produced through AM instead of turning are negligible. So looking at that aspect, using AM instead of using turning would not create any problems.

Q3: How does the shape of the BOR-element affect the function?

It is important to be able to meet the set tolerances of the shape of the BOR-element, especially in regards to the radius of the outer shape.

Appendix J – Interview with Joakim Åhlgård (previously Karlsson), SP

Åhlgård works at SP and takes part in the project OPTIPAM. Åhlgård possesses a PhD in additive manufacturing, mainly focusing on the EBM technique.

Q1. Please tell us a bit about yourself, what kind of background do you have and what is your connection to AM?

I have a PhD in Arcam's technique, the EBM-technique that you probably have heard of. I have also touched upon the other techniques in a more indirect way since they are very much alike. That is the background I have involving this.

Q2. Could you please explain the project "Optimerad produktionsprocess för additiv tillverkning, OPTIPAM" (Optimized production process for additive manufacturing)?

I suppose Sofia (Editors remark: Sofia Målberg) has talked about that?

Q3. In the description of the project OPTIPAM the "3rd industrial revolution" is mentioned. What is the 3rd industrial revolution for you?

That I can discuss a bit. Why have we written that and my thought around it? It is kind of what people are talking about, this industrial revolution, and there is a lot of talking about it being precisely that. It is kind of like if you are looking at the technique it kind of turns the techniques one normally uses up-side-down when manufacturing like this. In the normal processes you start with a big piece of material and then you remove the material you do not want until you get your final product. Here it is the opposite; you start with nothing and simply add the material you want. This leads to a completely new way of thinking. Partly in the way you design your products but also in the way you use the technique. There are completely new possibilities and also some different limitations. For example you do not have any cutting tools and you do not have to plan for where they need to go in and out, you also do not have any "angle of release" when you consider molding instead you have different possibilities and limitations.

But then there is the logistics as well. You talk a lot about this being the 3rd revolution since you have the possibility to have the production closer to the organization. In the long run the belief is that it will be possible to place the production close to the user. For example when it comes to tool manufacturing it is placed in low cost countries such as China and they have become huge within this field. But in this case it would be more competitive to "bring the production home". Basically the only thing you need is your digital file that you are able to print what you need, your final part.

That is kind of how we have interpreted it too. It is possible to come much closer to the customer.

Exactly, that is kind of what the idea is. If you have a product that you sell in many countries you might not need to have the whole production centralized instead you can change what you manufacture with the machines and there is no reason to centralize since you can manufacture different product in the same machine at the same time.

Q4. As with all production methods AM brings along both new *possibilities* and *limitations*. What are your beliefs these are? Are there some points that are more important than others?

It is kind of what we touched upon earlier, the thing with that you start off with nothing and build from that. The rest depend on what kind of technique you are using. But a lot of this involves the fact that you can easily make iterations. You do not need to create a new tool for every part that you want to print. Let us say you want to make a plastic detail with injection molding, you will need a tool. Once you have developed the tool it is very expensive to make changes in the design of the plastic detail. That problem also applies for casting; you have to make a whole new casting mold if you change the design of the product. In this lie a lot of possibilities for making changes.

Then we have this with adjusting the product. All products do not need to look the same. Today it is more focus on mass production, when all parts look the same there is money to make. But here you have a possibility to make them personal, i.e. you can customize them for the user. For example if you look at medical technology the development of 3D-technology has come very far and that is partly because of the need for customization for each patient. Instead of having a standard implant that suits everybody okay it is possible to print an implant that is customized for the individual patient. Those are some of the things that are the advantages.

Another thing is that you can control the microstructure on a completely other way than before. There are research results that show on micro structure level that the properties are different in different parts of the material. If you want one part of the product to be softer it is possible to control the microstructure to get a softer edge.

Then we have the advantage of manufacturing geometries that in many cases are completely impossible using conventional manufacturing processes. What I also think of are the so called network structures, it kind of looks like 3D-chicken wire.

Yes, we have seen some pictures of it at least.

It exists, and it is possible to use it. This kind of customized structure is completely impossible to manufacture with other processes. It can be adjusted depending on different properties that that are wanted. If you want it to only flex in one direction and be stiff in the other, in theory that is. In some papers they have been able to prove that it is possible although there are no products using it today.

We were thinking of the microstructure and how it affects the grain boundaries and so on. How is it affected by AM?

When it comes to printing you usually print in titanium. Usually Ti4Al6V, which is 6 aluminum and 4 titanium. When you look at both SL (editors remark: selective laser) and EBM that are the most specific for 3D printing of titanium it is a much, much finer microstructure compared to mainly casted material. You have a small laser electron beam that melts and you have a lot of material around so that you get a fast cooling process, which makes the microstructure fine. It affects the tensile strength; the creep limit tends to be worse with fine microstructure. With that said it depends on the application but overall the strength tends to be better for 3D printed material, especially nowadays.

Is the electrical conductivity affected by this?

No, I do not know anything about this. Nowadays the research has come so far that one do not risk to get too much space in-between the material, instead it is complete melting. It is not sintering anymore but complete melting. So the material density is approximately 100%.

Q5. You have mostly studied Arcam's methods. How are the possibilities and limitations different between the different Arcam methods (e.g. SLS, EBM). Are there any differences between the methods?

Yes, there are some differences. How the processes are built is somewhat different. The electron beam you have to use in vacuum while the laser processes are run with a flow of inert gas. So there is a difference which affects the risk of contamination for oxygen. It is partly solved for the laser though. Then there is a difference if you have a lower effect in the laser beam but it is also very slow. EBM control the beam with magnets while the SL is controlled with a mirror that has to be mechanically moved. This makes the SL a bit slower.

These two aspects are the reasons for why the EBM process is run warm. With help from the electron beam you heat up everything including the area you are going to print and the rest of the printing chamber. The whole powder bed is heated up to approximately 700 degrees Celsius and it stays there during the rest of the building time this takes away a lot of the residual stresses.

There are a lot of advantages with laser too, for example the surface finish is far better than with EBM, partly because it uses smaller powder but also because of the melting process.

Q6. We have understood that the beam reaches three layer of the powder bed, is that correct?

Yes, exactly, it is kind of the same. Since you have the powder bed and there is powder everywhere and when you shoot with the beam and the powder melts the powder grains that are close to the beam are partly melted. There is some difference there. The laser processes uses far finer powder around with 20µm diameter while EBM has 50-100µm.

Yes, there is some difference. The support structure is needed with angels above 30º; does that differ from the printing methods?

Mostly it is the same. I believe that Arcam would cope with less support due to the 700ºC in the whole chamber during the process. It is better packed and gives support itself. But if you do not have enough heat transport I would say that it does not matter when it comes to support structures.

Our project is about creating a method for adjusting the existing products to be produced by AM instead of conventional methods. Do you know any research with similar research questions?

In general it is what everybody is doing now. In the long-run I assume the companies would want to start investigating the but there are no examples of research studying the same thing. Not that I know of.

Q7. In your project you touch upon "Design for AM". This could be related to what we are studying. How do you work with this?

We have a post graduate who studies the possibilities and limitations that exist. That is what work we do in this project involving this. We look at some parts, such as, how thin walls can we have before we get problems?

How should you think when you design then? Instead of thinking of release angles or toolpath you need to think about support structures and how to remove the powder.

Q8. You also mention development of nondestructive testing methods in your project description, can you elaborate on this?

The thought with nondestructive testing methods is that if you can manufacture advanced geometries with 3D printing like for example encased cooling channels and 3D-chicken fence. Then the question is: how do we inspect these? How do we know that what we print is what we drawn in the beginning? And how do we know that our interior structure is intact? The classic way is that you destroy the product in order to look at it although that is not a very good quality check. Then you have to make guesses like "these 100 are manufactured in this way and we did not find any errors on them therefore number 101 must be good as well". For this matter we have started to look into CT-scanning in order to x-ray the product and evaluate what the inner structures look like.

Q9. Do you have any questions, inputs or other topics that you would like to talk about?

No, I think that you have chosen a good topic. I myself I think that 3D printing is fun. If you are able to send me a digital copy of your report it would be really interesting to read. And it you have any questions along the way do not hesitate to contact me.

Appendix K – Material and machine data

This appendix contains data for the material AlSi10Mg but also for the machine EOS M 290.

Table 1 - Components for AlSi10Mg

Al	Si	Fe	Cu	Mn	Mg	Zn	Ti
Balance	9.0-11.0	0.3	0.03	0.001-0.4	0.2-0.5	0.1	0.15

Table 2 - Technical data of the EOS M 290for AM production, (EOS, 2015)

Technical Data EOS M 290	
Building volume	250 mm x 250 mm x 325 mm
Laser type	Yb-fiber laser, 400W
Precision optics	F-theta-lens; high-speed scanner
Scan speed	Up to 7,0 m/s
Focus diameter	100 µm
Power supply	32 A
Power consumption	max 8,5 kW / typical 3,2 kW
Nitrogen generator	Integrated
Compressed air supply	7000 hPa, 20 m^2 / h
Number of available materials	6 types
Dimensions	
System	2500 mm x 1300 mm x 2190 mm
Recommended installation space	min 4800 mm x 3600 mm x 2900 mm
Weight	Approx.. 1250 kg
Build volume	250 mm x 250 mm x 325 mm
Data preparation	
Software	EOS RP Tools, EOSTATE, EOSPRINT; Materialize Magics RP with SG+ and further modules
CAD interface	STL Optional: converter for all standard formats

Table 3- General process and geometrical data from EOS SLS machine, for EOS Aluminum AlSi10Mg, (EOS, 2015)

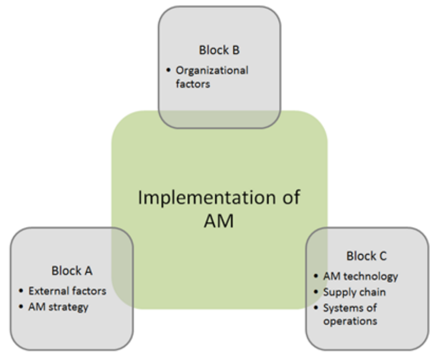
Typical achievable part accuracy	100 µm
Smallest wall thickness	approx. 0.3 – 0.4 mm
Surface roughness, as built, cleaned	R_a 6 - 10 µm, R_z 30 - 40 µm
- after micro shot-peening	R_a 7 - 10 µm, R_z 50 - 60 µm
Volume rate	7.4 mm^3/s (26.6 cm^3/h)
Relative density	approx. 99.85 %
Density	2.67 g/cm^3

Table 4- Summary of mechanical properties, data from EOS SLS machine, for EOS Aluminum AlSi10Mg, (EOS, 2015)

	As built	**Heat treated (300 ˚C)**
Tensile strength (1)		
- in horizontal direction (XY)	460 ±20 MPa	345 ±10 MPa
- in vertical direction (Z)	460 ±20 MPa	350 ±10 MPa
Yield strength		
- in horizontal direction (XY)	270 ±10 MPa	230 ±15 MPa
- in vertical direction (Z)	240 ±10 MPa	230 ±15 MPa
Modulus of elasticity		
- in horizontal direction (XY)	75 ±10 GPa	70 ±10 GPa
- in vertical direction (Z)	70 ±10 GPa	60 ±10 GPa
Elongation at break		
- in horizontal direction (XY)	9±2 %	12±2 %
- in vertical direction (Z)	6±2 %	11±2 %
Hardness [7]	approx.. 119 ± 5 HBW	
Fatigue strength		
- in vertical direction (Z)	approx. 97 ± 7 MPa	

Appendix L – Pamphlet for the ETAM method

ETAM



A

When starting the implementation process of additvie manufacturing, make sure that there is a value for the customers. Does additive manufacturing suit the over all strategy?

B

At this point the focus is on mapping the needed and available resources. This includes workforce experience, software etc.

C

C1

This part is in two parallell steps. A product analysis sets the requrements that are vital for the function of the procuct.

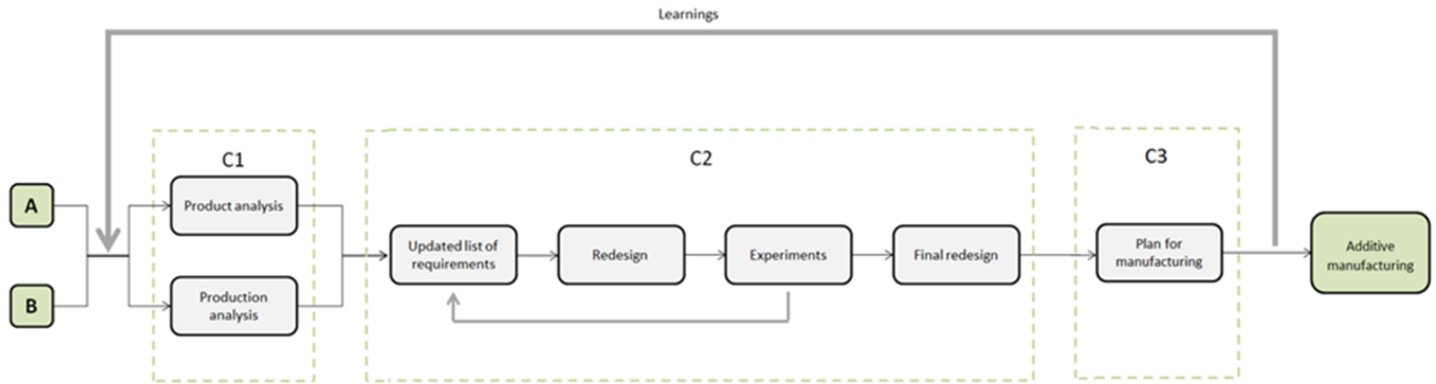
The constraints of the production needs to be mapped. What specific method should you use, and how does this effect the requirements on your product?

C2

This part is an iterative process that starts with combining the requirements from C1 and all other requirements are removed. Based on this the product is redesigned and tested. Topology optimization and FEM analysis. This step can also contain possible prototypes.

C3

It is then time to decide exactly how the product is going to be manufactured: in which angle, the number of products per batch etc.



A result of the Master thesis project Method for evaluating and transformation for additive manufacturing
by Linn Hedström Kuosmonen and Pamelina Olsson
Chalmers University of Technology, Gothenburg, 2015

Appendix M – Huray model analysis

Andreas Wikström executed the following calculations on request from the thesis authors.

The loss-calculations were performed in the simulation program Ansys HFSS, which is a 3D FEM solver. Two calculations were performed. One was for an ideal completely smooth surface of a tip. The other is with a surface roughness which has Rz = 35 um, Rxy = 8 um.

In Ansys HFSS, a model of the surface structure is created through the boundary conditions 'finite conductivity boundary'. In this procedure the Hurray-model was used with the above-mentioned values of surface roughness. The Hurray model is created to describe the losses that can occur in copper foil layers that have been created through electrodeposition used in printed circuits boards, because of the circuits' not completely even surfaces. The model that the software uses is not built to handle the surface roughness that AM produces, which means that there is uncertainty in the calculations. The surface roughness of 35 micrometers, which is a factor 70 higher than for PCB copper. This means that it is not certain that this model can describe the effects of a surface structure created by 3D printing will have on losses in a signal. The calculations in HFSS gave the following results, when the effect sent into the system in the simulation was 1W.

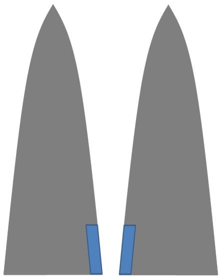


Figure 2- A simplified visualization of where on the BOR-elements the surface roughness is the most vital for the function connected to conductivity, which is marked with blue

Table 3 - Results from Ansys HFSS simulation of losses in signal perfomed by Anderas Wikström at SAAB EDS for the master thesis project

	10 GHz	**18 GHz**
Losses in the BOR-element [W] Ideal, smooth surface	0.0062	0.0163
Losses in the BOR-element [W] Rz = 35 um, Rxy = 8 um	0.00806	0.0188

The difference in signal loss at 18 GHz is 2.5 mW, as can be seen in table 3. This corresponds to a 0.01 dB increase in transmission losses. This can be considered a negligible difference. Since the calculations showed that the losses were so small, it was especially relevant to investigate the validity of the models applied to this specific situation. Therefore, the same simulations that were conducted on the BOR-element were applied on a larger object, which could be approximated to a cable, with the length of 100 mm. This resulted in somewhat more noticeable changes in the signal losses. This indicated that AM should not be used for larger or mainly longer objects where the conductivity is a vital function. It is important to remember that the BOR-elements, because of their rounded shape and the way they are placed in a pattern, the losses connected to the surface roughness only really apply to the bottom of the elements, as is illustrated in figure 2.
Based on this model the BOR-elements are 'short' enough so that the losses due to surface roughness in fact are negligible.

Appendix N – Lists of requirements

This appendix contains the updated lists of requirements for iteration II and III.

List of requirements II with changes marked in bold. Rating 10 is the most important requirement, rating 1 is low importance and 0 is not a requirement at al. A lower need for an inner support construction and a ditch as a new requirement are the new changes.

List of requirements III, changes marked in bold. Rating 10 is the most important requirement, rating 1 is low importance and 0 is not a requirement at al.

Table 2 – Updated list of requirement II

	Requirement	Rating
Product specific requirements	Same outer geometry	10
	Assemble possibility	10
	Transporting electrical signals	10
	Weight reduction	10
	Inner support construction	**0**
	Withstand outer environment	10
	Ditch to concentrate forces	**6**
Production specific requirements	Outer wall thickness: 2mm	10
	Other wall thicknesses: 1.5 mm	10
	Possibility to remove excess powder	9
	Maximum over hang: 30º	8
	Withstand outer environment	10
	Cost	7
	Surface roughness	**8**

Table 3 – Updated list of requirement III

	Requirement	Rating
Product specific requirements	Same outer geometry	10
	Assemble possibility	10
	Transporting electrical signals	10
	Weight reduction	10
	Inner support construction	0
	Withstand outer environment	8
	Ditch to concentrate forces	6
Production specific requirements	**Outer wall thickness: 2 mm**	**0**
	Other wall thicknesses: 1.5 mm	**0**
	Manufacturing resolution limitations	**8**
	Possibility to remove excess powder	9
	Maximum over hang: 30º	8
	Withstand outer environment	8
	Cost	7
	Surface roughness	8

Appendix O – Weighing of prototypes

The protoypes were weighed in order to find out the true weight of the elements but also in order to compare the reality to the expected weight from the CAD model.

Table 7 - Weighing result

Wall thickness	Test 1 [g]	Test 2 [g]	Avrage weight [g]
1 mm	7,8898	7,8898	7,8898
1 mm	8,4912	8,4911	8,49115
1 mm	7,638	7,6377	7,63785
1 mm (H)	7,8906	7,8906	7,8906
1.5 mm	9,4345	9,4341	9,4343
1.5 mm	9,6734	9,673	9,6732
1.5 mm	9,6738	9,6734	9,6736
1.5 mm (H)	9,7413	9,7415	9,7414
2 mm	11,2335	11,2537	11,2436
2 mm	11,1119	11,1119	11,1119
2 mm	11,4239	11,3528	11,38835
2 mm (H)	11,4238	11,4238	11,4238
2 mm (T)	11,5423	11,5424	11,54235

H=Two halves

T= After-treated by turning

Table 8 - Weight comparison

nr	BOR-element	Theoretical weight (g)	Weight compared to nr 1	Weight compared to nr 2
1	Solid (without guiding holes)	19,770	100%	113%
2	Solid (with guiding holes)	17,565	89%	100%
3	Wall thickness 2 mm	11,710	59%	67%
4	Wall thickness 1.5 mm	10,027	51%	57%
5	Wall thickness 1.0 mm	8,169	41%	47%

Appendix P – Pugh matrix analysis

Below follows a weighing of the remaining concepts. The table indicates that Concept 6 with 1mm wall thickness is the most suitable.

Table 3 - Pugh matrix analysis of the original concept, the three concepts with different wall thicknesses and a fourth concept with after-treatment.

	Rating	Original design	Concept 6 (2 mm)	Concept 6 (1.5 mm)	Concept 6 (1 mm)	Concept 6 (after-treated)
Same outer geometry	10		0	0	0	0
Assembling possibility	10		0	0	0	0
Transporting electricity	10		0	0	0	0
Weight reduction	10		+ (10)	++ (20)	+++ (30)	+ (10)
Withstand outer environment	8		0	0	0	0
Enabling concentration of forces	6		+ (6)	+ (6)	+ (6)	+ (6)
Manufacturing resolution limitations	8		0	0	0	- (-8)
Eigen frequency	8		+ (8)	++ (16)	+++ (24)	+ (8)
Possibility to remove excess powder	9		+++ (27)	++ (18)	+ (9)	+++ (27)
Maximum over hang: 30º	8		0	0	0	0
Surface roughness	8		-- (-16)	-- (-16)	-- (-16)	0
Summary			**45**	**53**	**61**	**53**